NEUROLOGICAL BASES OF THE TEMPORAL ORGANIZATION OF SPEECH

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I. INTRODUCTION

While speech appears as a linear phenomenon when recorded at the eardrum or by a microphone, it is more useful to think of it as representing multiple, encoded levels of information. In this view, the problem of understanding speech can be seen as a problem of understanding the sequence of encoding processes that give rise to the ultimate speech signal.

The process of encoding implies an interaction between *content*, *processing*, and *apparatus*. "Content" is concerned with the "message," or the "transmitted information" contained in the signal; "processing" relates to the encoding operation; and "apparatus" relates to the physical substrate supporting the encoding process. This substrate (articulator shape, biological and dynamic limitations) circumscribes the limits of the final acoustic signal, while the rules affecting "processing" specify the modulations used to encode semantic "content."

For example, physical limits on vocal fold dynamics determine the maximum *rate* of change in fundamental frequency (a biological limit), while language-specific rules relating to interrogative, declarative, or exclamatory mode (a processing rule) determine the *direction* of change within a frequency contour.

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Finally, the interrogative, declarative, etc. *sense* of the utterance constitutes the semantic part of the message (the content).

The present article bears primarily on "apparatus" and "processing." There are many reasons to believe that knowledge about these aspects of the encoding operation is used by human speaker-listeners during encoding and decoding. Such knowledge can also be used to direct automatic speech recognition algorithms towards maximally informative aspects of the signal. Research in this domain thus promotes both our understanding of human functioning and our attempts to simulate human functioning.

II. A SHORT OVERVIEW

The duration of various segments of speech is subject to a number of influences. At the prosodic level, syllables are typically lengthened when stressed or accented; at the phonemic level, the duration of a sound is often part of its distinctive feature pattern; at the coarticulatory level, the delay between articulatory actions is a crucial aspect of speech execution; finally, at a general motoric level, intervals between syllable nuclei are largely a function of speech rate and rhythm.

In outlining the multiple levels of temporal encoding, we attempt to follow the likely processing path centrifugally, and attach each processing level to a likely neurological processing site. Throughout this discussion it is understood that purported processing levels and processing sites retain a largely hypothetical status.

This overview is based upon a number of MEDLINE searches, and on an extensive review of the speech motor control impairment literature going back to 1966 (Keller et al., 1987a; 1987b). However, only a few representative studies are summarized here. The present overview is meant as a summary of the main concepts, not as an exhaustive review of the field.

III. PROSODIC EFFECTS AND RIGHT/LEFT HEMISPHERE PROCESSING

Prosodic variations are an essential part of the encoding of a wide variety of communicative and linguistic concepts (declarative vs. interrogative intonation, semantic emphasis, paralinguistic indications of approval/disapproval etc.). To the ear, prosodic variations appear as tone or intonational changes, or as variations in accent or stress pattern. Physically, prosodic contrasts are typically encoded in the signal by increases and decreases in fundamental frequency (F_o), voice amplitude and syllable duration.

Before discussing the neurological bases of these three parameters, a few words are in order concerning their mutual relationship. Generally, it is supposed

that the three parameters are in categorical—if not necessarily linear—correlation. That is, stressed syllables are usually considered to be characterized by relatively higher F_o, greater intensity, and increased duration in comparison to unstressed syllables (Malmberg, 1956; Lieberman, 1960; Fry, 1968). Such acoustic effects probably reflect articulatory gestures for stressed syllables that are longer in duration and spatially more extensive than those found in unstressed syllables (Ostry, Keller and Parush, 1983; Van Summers, 1987).

However, most studies have examined these effects over different stimuli, different speakers, and/or different stress categories. In a recent study performed in our laboratory with French-language speakers, stress was manipulated using the same repeated CV syllable (e.g. pà:papà:pa). The expected correlation between F_o, amplitude and duration was confirmed only for across-stress comparisons (i.e. when comparing stressed with unstressed syllables). *Within* the stressed condition, significant *negative* correlations were found for the relation syllable duration-F_o, as well as for the relation syllable duration-amplitude (Figures 1 and 2). Apparently our French speakers maintained a careful balance between syllable duration and the F-amplitude complex when communicating main stress, reducing duration with greater F_o-dB values, and increasing duration with smaller F_o-dB values. No such tradeoff was evident in unstressed syllables, where duration behaved in tandem with F_o-dB (Alain and Keller, 1990).

This partial dissociation between duration on the one hand, and the F_o amplitude complex on the other hand, raises the classic issues of modularity. Does the brain exert joint or separate control over F_o, voice intensity and duration as it attempts to convey such prosodic elements as stress or intonational modulation? If control occurs in separate functional modules, is the separation so great that it translates into differential impairment subsequent to discrete brain lesions?

Although a number of brain lesion studies have studied the neurofunctional bases of F_o, there are few hints in the literature of the relationship between duration and Fo (or amplitude). A number of studies indicate that fundamental frequency variations related to prosody are processed primarily by the right hemisphere (e.g. Smith, 1966; Dordain et al., 1971; Van Lancker, 1980). Also, a series of studies—which I shall discuss in the following paragraph—point to the crucial involvement of the opposite hemisphere in the processing of certain types of duration. It is thus indeed possible that the observed dissociation for duration and Fo have a neurofunctional basis.

The aforementioned recent studies have examined the neurofunctional basis of Fo in detail. Ross and Mesulam (1979) and Ross (1981) present a number of cases of relatively well-localized lesions in the anterior, medial and posterior right and left hemispheres that suggest:

Figure 1

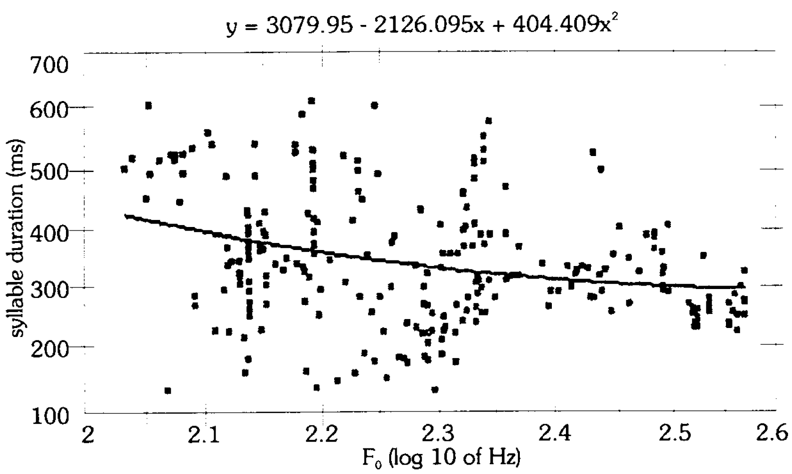

Figure 1: Negative correlation between fundamental frequency (F_o) and syllable duration in a repeated CV syllables experiment (normal subjects, stressed syllables only). F_o is the log10 of the maximum fundamental frequency in the vocalic portion of the syllable, and syllable duration is calculated as the vocalic portion of the syllable. Based on Alain and Keller (1990).

(a) that lesions of the anterior portion of the right hemisphere selectively impair prosodic aspects of speech[1], while lesions of the anterior portion of the left hemisphere selectively impair the propositional aspects of speech;

(b) that the posterior regions in both hemispheres are distinguished from the anterior speech regions by their strong involvement in the receptive aspects of speech, again according to the distribution: prosody/right and propositional speech/left.

[1] Ross and his colleagues actually identify "affect" encoded by the prosodic manipulation as the active component associated with the right hemisphere. However, a close reading of the literature indicates that right hemisphere localization is also (if not more often) compatible with the processing of the acoustic Fo component of messages that encode "affect" by various manipulations of prosody. At the very least, RH localization of the acoustic components of prosody is more easily demonstrated than localization of affect, because acoustic measurements are more easily performed.

Figure 2

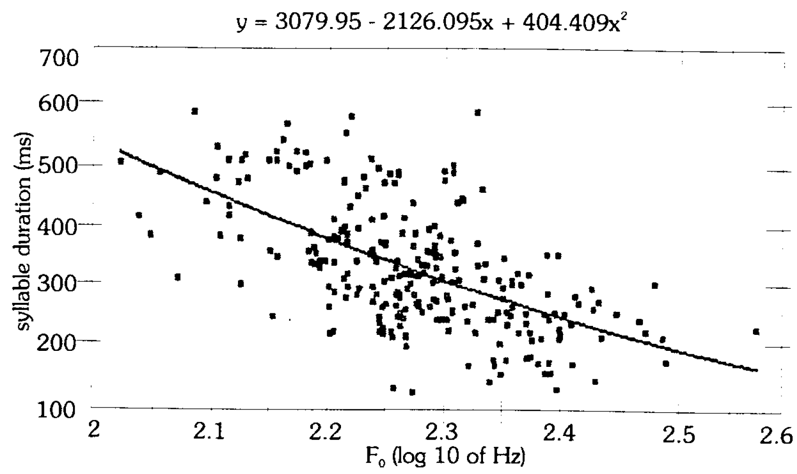

Figure 2: Negative correlation between relative dB and syllable duration in a repeated CV syllables experiment (normal subjects, stressed syllables only). Relative dB is the difference between threshold amplitude and maximum amplitude in the syllable, expressed as dB, and syllable duration is calculated as the vocalic portion of the syllable. Based on Alain and Keller (1990).

Later studies have largely been in support of these findings (Shapiro and Danly, 1985; Ross et al., 1988).

A study that has reported contrary findings—"the ability to convey linguistic stress appears preserved in RHD patients" Behrens (1988:125; see also Behrens, 1987)—involved declarative sentences containing a semantically emphasized word, i.e. productions that probably incorporated less pronounced prosodic manipulations than those of the previously cited studies.

Ross et al. (1988) present perhaps the most extensive and most rigorously controlled research into RH localization of prosodic effects. Epileptic patients were asked to produce the sentence "I'm going to the other movies" with different types of "affect"—neutral, sad, happy, surprised, bored, angry—prior to, and while, injected with sodium amytal in the right hemisphere. In the injected state, the fundamental frequency modulation was significantly reduced as compared with pre-injection levels, while durational (and amplitude-related) aspects were unaffected.

"Duration" refers to the total time of the sentence, and "F_o modulation" refers to a number of parameters measuring F_o "flatness" in comparison to pre-injection production. This is clearly in support of the hypothesis that fundamental frequency is encoded nearly exclusively by the right hemisphere, while duration is encoded primarily by the left hemisphere.

However, it must be emphasized that the reviewed experiments have barely scratched the surface of the question. To date there has been no thorough exploration of the neurofunctional bases of F_o and duration over longer and shorter stretches of speech. Moreover, most studies by far have been performed on English (one exception: Gandour and Dardarananda, 1984).

IV. PHONEMIC AND COARTICULATORY EFFECTS AND ANTERIOR LEFT HEMISPHERE PROCESSING

At the level of segmental (phonemic) processing, it is assumed that speakers seek to encode linguistically relevant contrasts, i.e. contrasts that distinguish between various possible messages. For example, the words "bet" and "pet" are distinguished by a single initial phoneme. Articulatorily, this involves among other things a manipulation of the delay (voice onset time: "VOT") between the opening of the lips and the onset of voicing for the vowel /ɛ/. Common phonemic contrasts that have known effects on delays in gesture activation or on segment duration are the voiced/unvoiced stop consonant contrasts, or the vowel length contrasts used in a large number of languages.

Considerations of signal processing load, of the likely upstream and downstream processes, as well as of the nature of normal and abnormal speech errors (Fromkin, 1973; Blumstein, 1973; Keller, 1975; 1978; Nespoulous et al., 1987) suggest that this processing level includes a major bottle-neck, where planned linguistic information is translated from buffered linguistic representations into a small group of serial processing streams, each of which is related to a specific neuromuscular output path (Keller, 1987). Processes preceding this bottle-neck are typically referred to as "planning processes, " while those downstream of the bottle-neck are known as "execution processes."

Much of this type of bottle-neck processing appears to occur in perirolandic areas of the left hemisphere. Motor speech disorders due to lesions in this area (Broca's aphasia) are characterized by errors predicted by the bottle-neck, including omissions and substitutions of phoneme-length speech segments. Also, such patients have in recent years been shown to suffer from a distinctive impairment in phonemic VOT's (Blumstein et al., 1980; Itoh et al., 1982; Shewan, Leeper and Booth, 1984; Ziegler, 1987).

In all of these studies, patients with suspected anterior left hemisphere lesions tended to show less systematic capacity to distinguish long from short VOT's than either normal subjects or patients with probable posterior left hemisphere lesions. In each tested language, VOT was associated with a phonemic differentiation. This deficit can be interpreted as an impairment in learned coarticulatory timing patterns associated with phoneme differentiation, where systematic delays in onset of activity of different neuromuscular output streams are no longer available to the patient (Keller, 1987).

This interpretation of Broca's patients' syntagmatic impairment can be related to the general observation that they are characterized by excessive slowness, i.e. what appears to the ear as slow, laboured speech (see e.g. Goodglass and Kaplan, 1972; Kent and McNeil, 1987), and that some such patients show excessive difficulty with consonant-consonant transitions (Luria, 1966). However, it remains that the learned delay impairment hypothesis is based on a relatively small number of studies nearly exclusively concerned with VOT distinctions. Also, measured VOT abnormalities may in fact be related to the patient's general motor execution impairment, and could conceivably have little to do with the paradigmatic or syntagmatic encoding of phonemic contrasts.

Such alternative hypotheses need to be ruled out through additional studies before the learned delay deficit hypothesis can be fully endorsed.

V. SPEECH RATE/RHYTHM AND FINAL OUTPUT PROCESSING INVOLVING THE CEREBELLUM

It is well-established that speech motor control is ultimately mediated by a cortical and subcortical motor system whose evolutionary origins relate more directly to respiration, deglutition and swallowing than to speech. The final output path in speech production thus involves a system that is likely to be less specifically related to speech encoding, and that probably shares major functional properties with other human motor systems.

Following this line of argument, certain aspects of speech control can potentially be viewed as instances of a more general type of motor control processing. In particular, actions that show pronounced behavioural and/or physiological similarities with other forms of motor control may fall into this category. For example, rapid, repeated movements—so-called diadochokinetic movements—can be produced indifferently by various limbs or speech articulators. One can thus hypothesize the timing scheme supporting such movements to be part of a super-modular ("general") human motor programming capacity, rather than part of a speech-specific motor system.

Figure 3

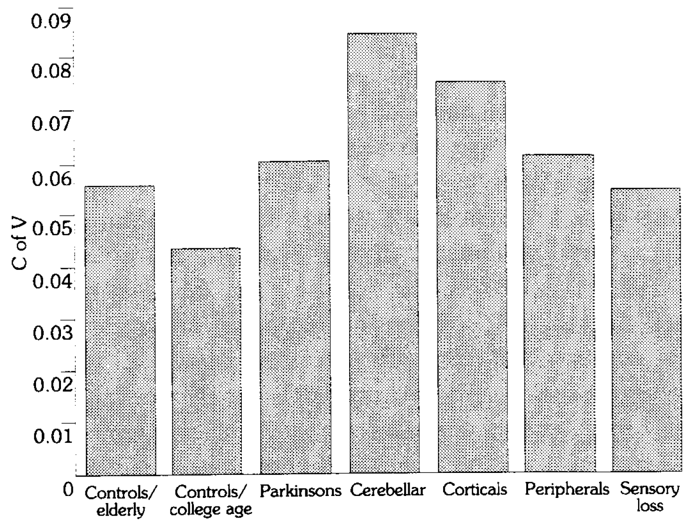

Figure 3: Variability in inter-tap intervals for patients with various types of brain lesions and two control groups,. Patients with cerebellar disorders showed the greatest inter-tap variability. Based in Ivry and Keele (1989).

Neuroanatomically, such generalizable aspects of motor control are thought to be mediated by a complex network of cortical and subcortical structures, involving the primary motor cortex, portions of the basal ganglia, the efferent motor pathways, the brainstem and spinal cord nuclei, as well as the cerebellum. Indeed, the cerebellum may well have particular responsibilities in the timing of "general" motor actions. Patients with cerebellar disorders show extensive timing impairment in diadochokinetic tasks, e.g. finger-tapping, reiterant speech (Grémy, Chevrie-Muller and Garde, 1967). Also, patients of this type show slowing in vowel and VOT production (Kent et al., 1979).

Problems of increased duration and time variability generalize to limb motor control. In a study involving three patient groups with various brain lesions and two normal control groups, Ivry and Keele (1989) found that the cortically lesioned and the cerebellar patients were the slowest tappers (together with normal elderly patients), and that the cerebellar patients show the greatest variability in inter-tap intervals (Figure 3).

The traditional counter-argument—that it is notoriously difficult to disengage motor execution effects from motor control deficits in motor speech disorders—is

Figure 4

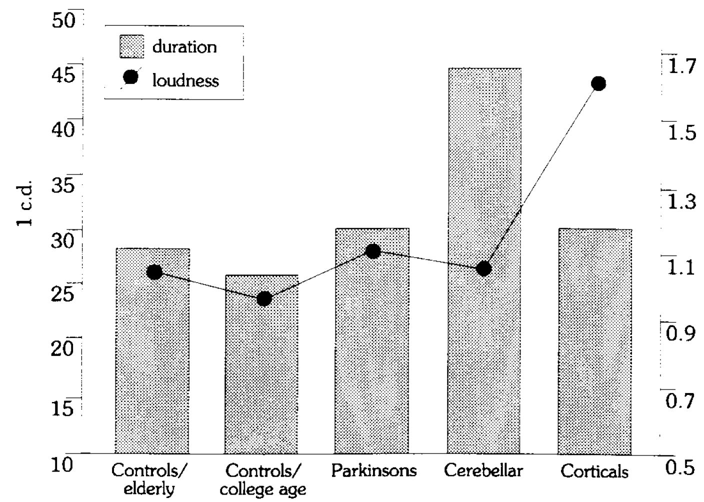

Figure 4: Performance on same/different duration and loudness judgement tasks. Cerebellar patients performed worst of all patients on the duration task, but did well on the loudness task. Based in Ivry and Keele (1989).

contradicted by recent experimental evidence of lesion-induced perceptual timing deficits, independent of motor impairment, in patients with cerebellar disorders. In a same-different judgement experiment, Ivry and Keele (1989) measured the ability to decide whether the second of two pairs of beeps was more or less closely spaced, or spaced at the same delay than a first set of beeps. They also used beeps that tested same/different loudness judgement. The results on the duration judgement task closely paralleled those of the motoric tapping task in that there were similar average impairments in the three patient groups and the two groups of normal subjects, with the cerebellar patients being the most severely impaired (Figure 4). At the same time, impairment in the performance of the loudness perception task differed from the impairment in time judgement, with cortical patients being the most strongly impaired.

This demonstration of an impairment of timing judgements with cerebellar lesion suggests that cerebellar timing disorders are independent of neuromuscular motor execution effects.

The results of a recent experiment performed in our laboratory suggest that such a cerebellar timing deficit can generalize to speech (Keller et al., 1990). In

Figure 5

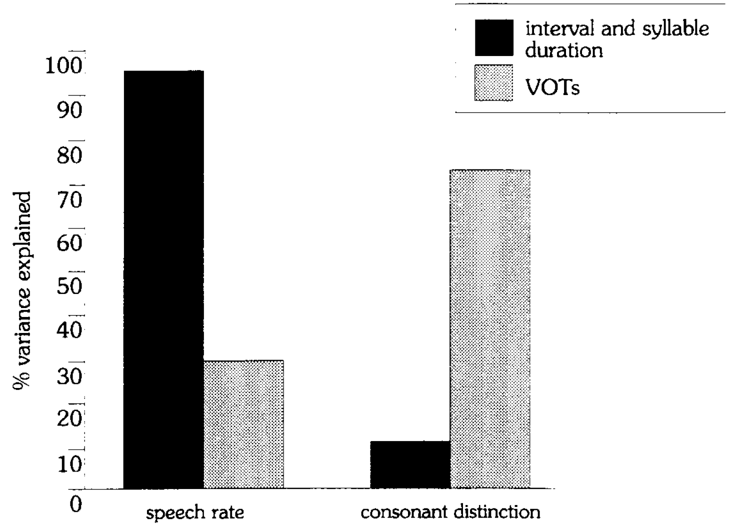

Figure 5: Performance by normal subjects repeated CV syllable production task. Speech Rate shows the best prediction for inter-consonant intervals and syllable durations; the phonemic consonant distinction between p, t and k shows the best prediction for VOT. Based on Keller et al. (1990).

keeping with the above hypotheses, we expected that in a repeated CV syllables production experiment, rhythm would be disturbed by cerebellar disorders, while VOT interarticulatory delay effects would be less affected. Thirteen dysarthric patients with cerebellar and/or spino-cerebellar lesions (mostly diagnosed as Friedreich's ataxia), and six control subjects were examined. Normal production followed a pattern established in a previous study (Keller, 1989): speech rate had excellent explanatory power for the variance of intervals between consonants and for the durations of vowels, with about 95 per cent of variance explained, but only moderate predictive power for VOT (about 31 per cent). Consonant distinction had the best predictive power for VOT's, with about 77 per cent of variance explained, but only moderate predictive power for the other measured durations, about 12 per cent (Figure 5).

Generally, patients showed a pattern of less specificity in the double dissociation: rate was less clearly associated with intervals and syllable durations, and phoneme distinction was less strongly associated with VOT (Figure 6). But in addition, an interesting skew occurred in the crossed predictions: there was an increase in the

Figure 6

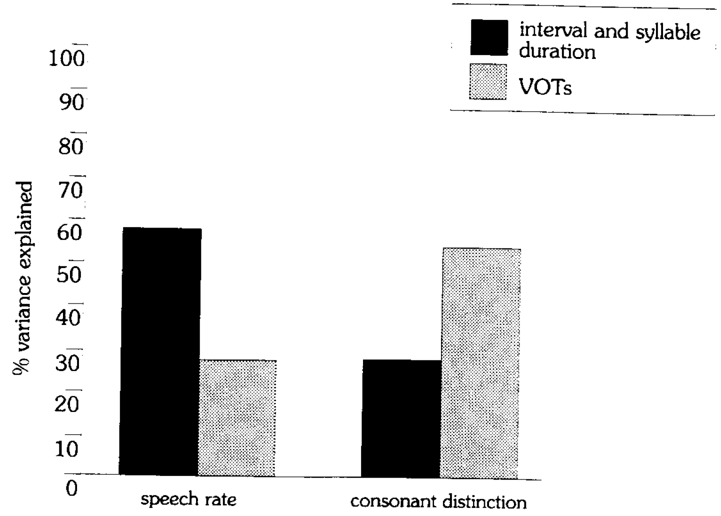

Figure 6: The performance of patients with cerebellar lesions on the same repeated CV syllable production task. Only the performance of six severely impaired patients is shown: results for seven moderately impaired patients are situated between severe and normal behaviour. The specificity of the predictive pattern is reduced and the "influence" of consonant distinction seems enhanced (see text) Based on Keller et al. (1990).

interval/syllable duration variance explained by phoneme distinction, but there was no corresponding increase in the VOT variance explained by rate. It may well be that this reflects patients' greater maintenance of control over phoneme distinctions (which we have argued are primarily negotiated by the left perirolandic cortex), contrasting with their diminished maintenance of control over rate distinctions which may well be effected by the cerebellum.

VI. USEFUL DIRECTIONS FOR FURTHER RESEARCH

After reviewing the existing literature on the neurological bases of speech segment duration, the gaps in our knowledge appear at least as wide as the hypotheses that appear probable or certain. Here are two examples:

(a) from a theoretical viewpoint, the differentiation between—at least—prosodic, phonemic, coarticulatory and rhythm predictors of speech segment duration is imperative. Yet most work on the neurological bases of duration has concentrated on VOT (a coarticulatory and phonemic predictor). Very little, if any, work has addressed the remaining predictors;

(b) from a neuropsychological viewpoint, the differentiation between various cortical and subcortical lesions is well-established. Yet practically no research has addressed systematic differences in the performance of various patient groups for each class of speech segment duration. Which are the groups that show the least control over the various types of speech segment duration? How do such potentially selective disorders fit into our current neurofunctional hypotheses of speech production?

This fertile area of investigation is largely underexplored. Duration is relatively easily and reliably measured in the speech signal, and the theoretical predictors of speech segment duration have been the object of fairly extensive investigations. It would be easy enough to fill in the large number of gaps in our present knowledge of the neurological bases of speech segment duration, by developing a test protocol that incorporates the pertinent durational predictors, and measuring deviance from the norm in a number of key patient groups. The results obtained would provide excellent information about the processing of various types of linguistic information at different levels of the brain. In this manner, our understanding of the entire speech production process would be reinforced, and could be related in a meaningful way to known neurofunctional distinctions.

Of course, care would have to be taken to dissociate as much as possible primary, secondary, and compensatory effects. A patient may shorten or lengthen a syllable for a variety of reasons, including insufficient control over rhythm, timing, or segment duration. Care is required, for example, in identifying the patient's syntactic or lexical retrieval problems that have secondary effects on duration.

Also, the present summary has concentrated on just three of the most important processing levels in speech production. Other levels—notably the sensory feedback level—have been left aside and would need more thorough exploration in a full research effort directed at disentangling the pattern of predictions of speech segment durations.

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