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THE SOURCE-FILTER MODEL OF SPEECH PRODUCTION APPLIED TO EARLY SPEECH DEVELOPMENT

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ABSTRACT

In order to understand the speech developmental process in infants from birth onwards, and design an instrument suitable to relate early infant sound productions to basic elements of adult speech, we tried to map the sensorimotoric development of the sound producing mechanism and possibly trace any systematics within the process. Subsequently we intend to describe the acoustic aspects of the sound productions within well defined motoric stages.

A method to study this developmental process was designed, based on the source-filter model of speech production. Within the framework of the anatomical and physiological capacities of the infant, source activities were described in aspects of phonatory development. Filter activities were represented by developmental aspects of articulatory movements. A breath group was used as a segmentation unit.

This method resulted in six clearly recognizable, sensorimotoric developmental stages in the infant's sound productions in the first year of life. Based on these results we tried to mark within the sound productions of one infant in his first year of life, each of the stages I-V by a number of acoustic features.

INTRODUCTION

Learning how to use lungs, larynx and vocal tract as the instrument for speech production, is an indispensable stage in the infant's developmental process toward adult speech communication. Initially a neonate's vocal activities are limited to crying and producing vegetative sounds, but in the course of the first months sound production develops considerably.

The discontinuity view, based on the structuralistic approach of Jakobson [3] who believed that no relation existed between the early infant's sound productions and the development of speech and language, is more and more rejected in favour of the theory of continuing communicative development toward adult speech communication. The growing interest in infant speech development, however, also puts on the stage the problem of how to describe the early sound productions. Since no linguistic system is acquired yet, phonological transcriptions imply all kind of problems. In first instance acoustic measurements make no sense either, if no framework is available to interpret the results. We thus opted for first mapping the sensorimotoric development of the infant's sound producing mechanism in well defined stages, and subsequently describing the acoustic aspects of the sound productions within these stages.

DESCRIPTION OF INFANT SOUND PRODUCTIONS

Since normally neonates at birth are well equipped with a complete and operational sound production mechanism, the development toward speech can be described on the basis of the movements of this mechanism. As in adults lungs, larynx and vocal tract make up the main constituents and this provides us with the possibitity to apply the source-filter model of speech production to the description of the infant's speech developmental process as well [11, 5]. Within this model of description, a breath group is used as a natural and manageable segmentation unit, providing the possibility to discriminate between crying and comfort sounds.

Source functions are expressed by various aspects of phonation. Here a basic distinction on source level is the distinction in either continuous or interrupted phonation.

All kind of filter functions can be represented by indicating the various movements within the vocal tract (see Fig.1, and furthermore [5] and [11] for more details).

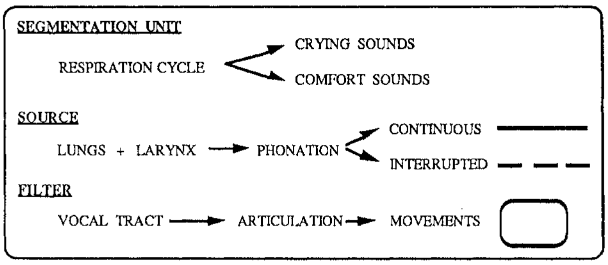

Fig. 1. Elements for the description of infant speech development based on source and filter aspects.

This very basic coding system, using only the source and filter elements as units, enables us to describe the development of the infant sound productions in the first year of life, considered from a sensorimotoric viewpoint. In this way we are not forced to apply rather inadequate linguistic transcription systems, i.e. transcription systems developed for the adult use of speech. Moreover, the development of movements within the sound producing mechanism can be compared now with the other motoric developmental courses in the first year of life [12].

Using our coding system we indicated six distinct developmental stages in the infant sound productions (see Table I), that are clearly recognizable after some training [5].

Table I. Developmental stages in the infant sound productions in the first year of life, based on the first occurrence of gradually more coordinated movements in respiration, larynx and vocal tract.

STAGE	AGE IN MONTHS	CHARACTERISTICS
I	0-1	Uninterrupted phonation without any articulatory movement within one breath unit.
II	1-2	Interrupted phonation within one breath unit, without any articulatory movement.
III	3-4	One articulatory movement within one breath unit, in combination with continuous (I) or interrupted (II) phonation.
IV	5-6	Seeming relapse: a strikingly large decrease of articulatory movements (III) and increase of uninterrupted phonation without articulation (II); at the same time, however, all kinds of variations in the phonatory domain with respect to intonation, duration, and intensity.
V	7-8	Reduplicated articulatory movements during one breath unit, in combination with continuous or interrupted phonation (III), together with all phonatory variations (IV), normally indicated as 'babbling'.
VI	9-14	Variegated babbling by combining all kinds of utterances of the preceding stages, more and more used only in certain situations, so that for the adult recognizable and meaningful 'words' occur.

A recent Swedish study [10], using the IPA transcription supplemented with a number of articulatory based annotations, presents an almost perfect agreement of their resulting stages with our previous findings [5]. One of the problems, however, when comparing results from various studies, as done in this Swedish work [10], is the difference in used terminology, often related to the (almost always subjective) transcription system applied.

For answering quite a number of research questions on early speech development (e.g. questions with respect to the universality of the speech developmental stages, with respect to the development of sound productions in hearing-impaired children, problems of identifiability of the language specific features in early speech development), it would be of great use if coding could be combined with objective acoustic foundations. But acoustic measurements should preferably be related to a framework of clearly distinguishable stages in the early sound development.

ACOUSTIC MEASUREMENTS OF INFANT SOUND PRODUCTIONS

If we phonetically define a syllable (as is generally accepted) as a continuum of human speech sound, consisting of a sonority maximum between two sonority minima, (or onset, nucleus and coda), our coding system provides us with the possibility to indicate those elements that constitute a syllable. Even in quite early sound productions consisting of interrupted phonation only, these requirements for a syllable are met (e.g.sounds like *uh-uh-uh, ah-ah-ah,* indicated by a broken line in Fig.1). Since articulatory movements (in Fig.1 indicated by a block) can be combined with, or come instead of phonation, early sound productions like *arra, hegg, uggu* can easily be represented as a one- or two-syllabic sound without the need to label the (vocalic) phonation part as an adult vowel and the articulatory part as an consonant.

As presented in Fig.2 it is possible to describe syllabic effects, irrespective whether they are produced by adult or by infant, using only basic coding units. In this way a bridging can be created between early infant sound productions and elements of adult speech. Moreover, this might be a good starting point for structural acoustic measurements, comparable with those used for adult speech.

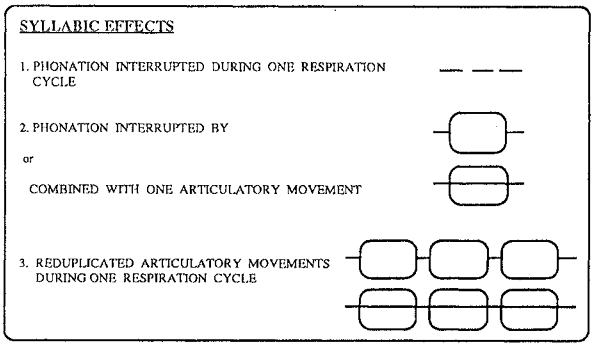

Fig. 2. Syllabic effects indicated by means of the basic coding units for the description of infant speech development.

Our attempts at bridging the gap between description of adult speech and tinfant sound productions are comparable with those of Oller [7], who introduced a metaphonological level between concrete phonetic/phonological transcription and acoustic/instrumental description, especially elaborated for what is called a 'canonical syllable'. He therefore suggests seven quantitative acoustical restrictions, although he admits that the "values are somewhat arbitrary" (see Table II). As soon as these canonical syllable requirements are met, a phonological transcription can be applied. A problem, however, is that even a number of adult syllables (like isolated vowels, and sequences with nasalized sounds or glottal interrupts), do not meet the canonical syllable requirements.

Although Oller's proposal is quite attractive to bridge the gap between acoustic and transcriptional approaches, it lacks the possibility to incorporate most of the early sound productions, viz. those produced in the first six months of life and is thus unsuitable to describe the developmental process, for normal as well as for speech handicapped children.

Table II. Short rendering of the acoustical requirements to be met by a canonical syllable, as suggested by Oller (1986).

	ACOUSTICAL REQUIREMENTS FOR A CANONICAL SYLLABLE
1	Difference between peaks (nuclei) and valleys (margins): ≤ 10 dB.
2	Peak-to-peak duration: 100-500 ms.
3	Full resonance nuclei (produced by periodic source and relatively open vocal tract).
4	At least one margin of low resonance and relatively closed vocal tract.
5	Smooth formant transition between margin(s) and nucleus; transition duration: 25-120 ms.
6	Intensity range: ≤ 30 dB.
7	F0 range: ≤ two-fold.

Because of the large anatomic changes in the vocal tract of infants at about four to six months of age, the sound producing apparatus of very young infants functions quite differently from that of older ones and of adults [1, 2, 4]. Before these changes, when the tongue is still massive, filling the whole mouth, and the nasal tract cannot be closed very well, the apparatus prohibits the production of fully-resonant sounds. This constitutes a number of constraints that hampers a complete comparison at any developmental age and with adult speech productions. So if quasi-resonant sounds of hearing-impaired children of eight months of age or older are compared to quasi-resonant sounds of two- or three-months-old infants [8], an improper comparison is made, since no attention is paid to the sensorimotoric developmental stage of the infants. For, since in a hearing-impaired child of nine months the production apparatus is just as mature as in a normal hearing infant of that age, the resulting quasi-resonant sounds cannot be attributed to the vocal tract as such, yet only to the *use* of it. So it is very important not to confuse the effect of hearing-impairment with that of immature, incomplete, or deviant anatomical growth [12]. Also in those cases where the infant sound production mechanism presents defects like in cleft palate infants, it is quite clarifying to compare both normal and deviant development of sound production in relation to the sensorimotoric stages [6].

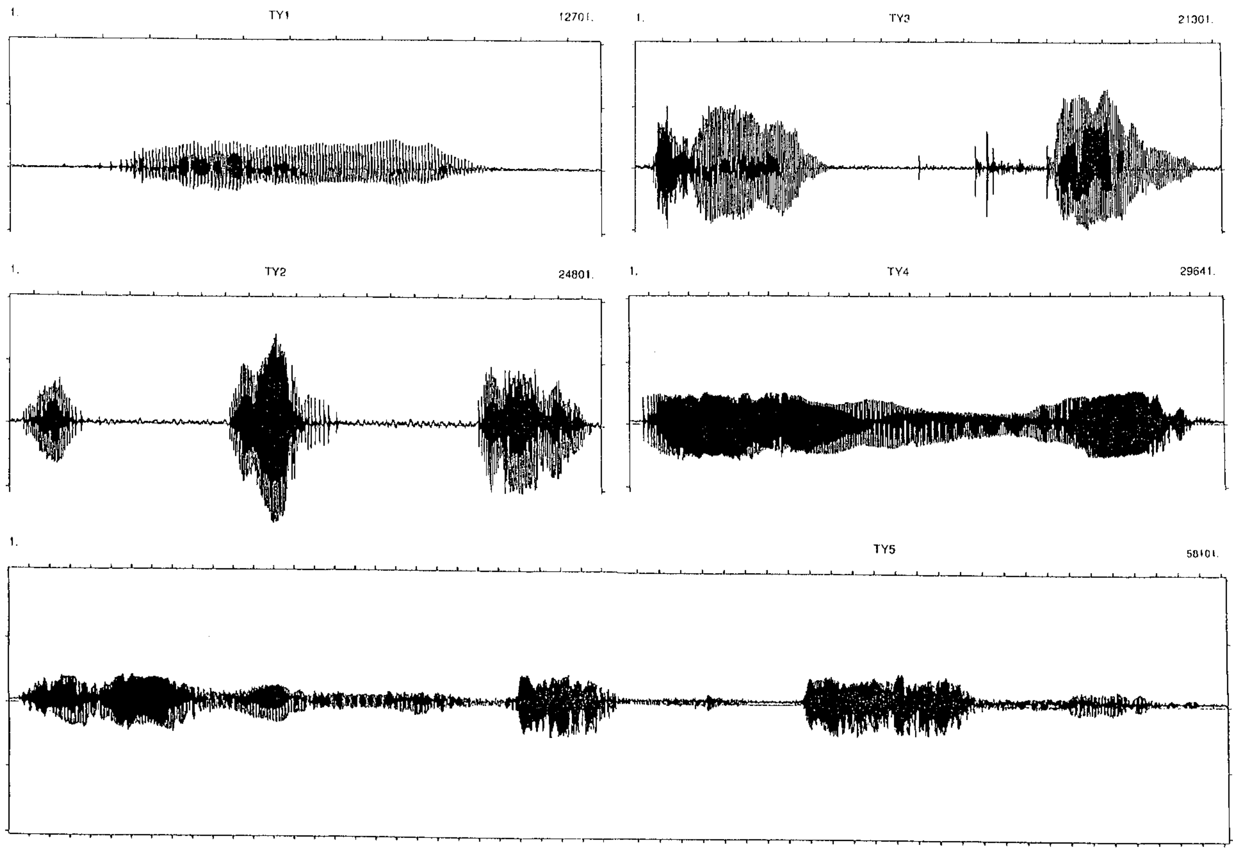

Fig. 3. Exemplary wave form representations for the developmental stages (I-V) in infant sound production, preceding the stage of word use.

So it is our aim to develop an instrument that is suitable for the description of sound productions in the first year of life of normal as well of (possibly) speech handicapped children, and related to sound characteristics of adult speech. Since the above mentioned six developmental stages are quite recognizable, we selected from weekly made audiorecordings of the sound productions of one infant (from birth until nine months of age) the first twenty utterances meeting the requirements for each of the developmental stages I to V. All selected utterances were lowpass filtered at 9.6 kHz and digitally stored on a microVAX II computer with a 20 kHz sample frequency and a 12-bit precision. Subsequently acoustic measurements were performed concerning duration, fundamental frequency and spectral energy distribution. Since at the moment of writing measurements are still in progress, we will only present here for each of the five developmental stages in infant sound production one exemplary wave form (Fig.3).

Finally the results will be compared with the requirements as formulated by Oller, and for each of the stages a set of characteristic parameters will be set up.

CONCLUDING REMARKS

Unlike Oller [7] who wants to match the acoustic measurements of early infant sounds with the requirements of a canonical syllable, we decided to match the acoustic measurements for each of the six sensorimotoric stages within the framework sketched above. In this way all stages are considered to be equally essential within the developmental process of sound production. Especially if one tries to design a speech training program, e.g. for severely hearing-impaired children [9], it is quite important to consider each of the stages as equally essential and to pay attention to all basic capacities. In the often neglected stage I the child has to learn to combine *breathing with phonation*. In stage II it has to train the *voice-onset control* and within this to structure *syllables on phonation level only*. In stage III the child has to master articulatory movements in combination with 'unarticulated' vocalic sounds, necessary for the later production of *consonantal* sounds. Although exercises on articulation thus start early in the developmental course, they never are isolated articulations. So this stage has to be characterised rather as practicing phonation in combination with articulation movements, or as structuring *syllables on articulatory level*. In stage IV all kinds of phonation variations are practiced, essential for the later production of *vocalic* sounds and for *suprasegmental speech aspects*. Finally in stage V all previous exercises are combined in *fully canonical units for mature speech*, whereas in stage VI these sound units are to be *matched to meaning*.

A model of infant sound development based on the source-filter elements of the human instrument for speech production, supplemented with acoustic characteristics, will hopefully provide us with an instrument suitable to relate early infant sound productions to basic elements of adult speech.

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