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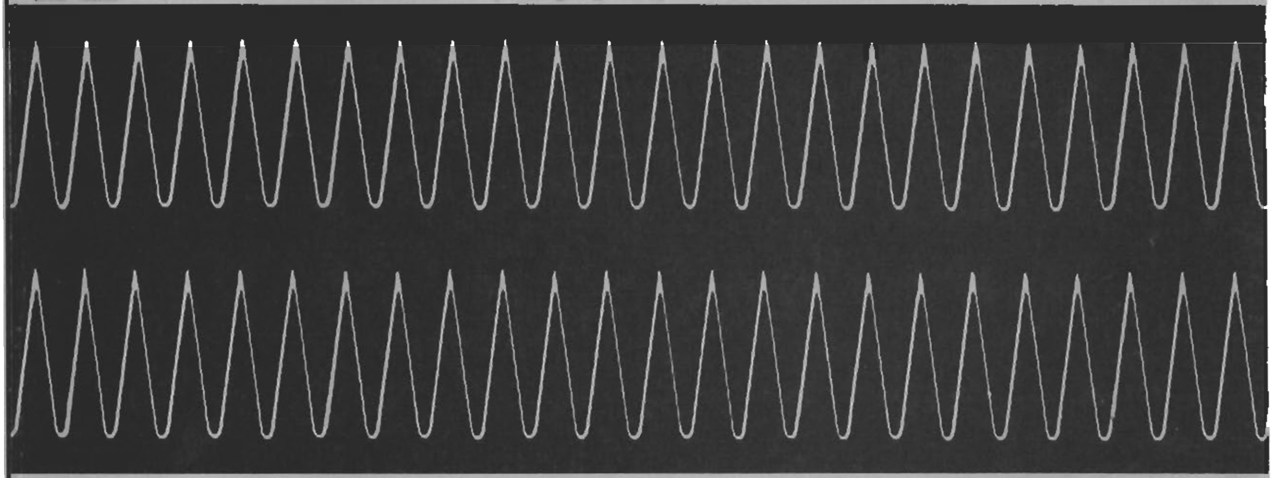
Speech and the Dentofacial Complex: The State of the Art

Proceedings of the Workshop



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PROCEEDINGS OF THE WORKSHOP
SPEECH AND THE DENTOFACIAL COMPLEX:
THE STATE OF THE ART

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Proceedings of the Workshop

Speech and the Dentofacial Complex: The State of the Art

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STATE-OF-THE-ART WORKSHOP ON SPEECH AND THE DENTOFACIAL COMPLEX

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FOREWORD

In recent years, the Oral-Facial Growth and Development Program of the National Institute of Dental Research has convened a series of workshops in three major areas: growth and development, cleft lip/cleft palate, and malocclusion. The purpose of these workshops is to analyze the current status of research and the need for future program development.

Over the past 10 years, the program has supported extensive research in cleft lip/cleft palate, with the rehabilitation of the cleft lip/cleft palate patient being the major focus. Since acceptable speech is one of the major goals of rehabilitation, research in oral communication in its broadest sense is involved. Furthermore, numerous other dentofacial problems are in need of interdisciplinary research involving speech scientists and dental investigators. Accordingly, since 1966 the National Institute of Dental Research has supported the activities of the Joint Committee on Dental and Speech Pathology-Audiology for the purpose of promoting cooperation between the professions of dentistry and speech pathology in the approach to research problems of mutual interest. The committee has representation from the American Association of Dental Schools and the American Speech and Hearing Association.

Because of program interests, therefore, it was decided to convene a workshop on speech and the dentofacial complex to make a critical evaluation of past and current research in speech as it relates to the dentofacial complex and to identify profitable areas for future research. This report, comprising the papers presented in the course of the workshop, is a valuable resource for program planning in the Institute. It is hoped that the report will also serve as a useful resource for the scientific community, especially those interested in conducting research in the area of speech and the dentofacial complex.

The Institute wishes to thank the planning committee, which worked closely with the Institute staff in planning the workshop; Drs. Spriestersbach and Irwin, who served effectively as cochairmen of the workshop; Dr. Fricke, who was so helpful in coordinating the effort; and the American Speech and Hearing Association for its excellent cooperation.

We also wish to give special thanks to the participants, who contributed the papers which make up this state-of-the-art study.

Seymour J. Kreshover, D.D.S., Ph.D.
DIRECTOR
National Institute of Dental Research

May 21, 1970

PREFACE

In June of 1969 the American Speech and Hearing Association was awarded a contract from the National Institute of Dental Research to conduct a State-of-the-Art Workshop on Speech and the Dentofacial Complex. The awarding of this contract attests to the significant interrelationship between the professions of speech pathology and dentistry. This interrelationship has been strengthened partly by the broadening base of substantive concerns which involve the fields of dentistry and speech pathology.

The dental profession has expanded the base of its concern, and coordinately, the breadth and depth of its professional training. Emerging from their earlier preoccupation with the mechanical arts, the dental sciences have begun to draw increasing sustenance from the basic health sciences. Accordingly, the technique-oriented practitioner of yesterday is today viewing the problems of oral health in the context of the total organism, sensing and responding within the context of the entire milieu.

Similarly, the profession of speech pathology has expanded its view. No longer are its practitioners satisfied to deal largely with symptoms, attempting to modify deviant behavior with pre-established routines which have proven to be somewhat efficacious with modal problems. Increasingly, it has seen the need to understand the anatomic, physiologic, neurosensory bases for the behavior with which it is concerned and the psychological bases for the behavior modifications it is able to achieve.

It was deemed appropriate, then, to conduct a State-of-the-Art Workshop involving these two professions since they are concerned with common body structures; since neither field is sure of the boundaries of its professional responsibilities and, therefore, the proper boundaries for its research and the training of its professionals; and since time and resources are in short supply. For any one professional discipline it is necessary, at regular intervals, to evaluate and describe the accomplishments of the past, to reexamine the activities of the present, and to project goals and directions for the future. When two disciplines are concerned with many of the same structures, processes, methodologies, and techniques as are speech pathology and dentistry, it is especially important that they approach problems of mutual interest with a full understanding of the state of the art in the other discipline.

In this regard, much remains to be done. The time lag between research findings and the implementation of these discoveries into clinical and training activities is a major problem for both dentistry and speech pathology. Within either profession specific examples of this problem could be mentioned. The problem is even greater, however, when the research activity is of direct interest to the training of one profession, but is conducted and published under the aegis of the other profession. In dentistry and speech pathology this is a frequent and recurring problem.

The purpose of the State-of-the-Art Workshop, then, was to attempt to shed some of our professional provincialisms, to determine where the two professions can combine forces, and to develop consensus about fruitful areas of research along with a sense of priority for that research.

Procedures

The overall plan for the State-of-the-Art Workshop and selection of the participants was made by an ad hoc advisory committee. The project director was in charge of administrative responsibilities relative to the conduct of this project. The committee met on two occasions prior to the first state-of-the-art sessions and originated a plan which called for a total of 20 selected participants who would prepare papers broadly categorized into three general areas, outlined as follows:

1. Development and Maturation of the Oral-Facial Complex: Normal and Abnormal
   a. Structural development of the neural, muscular, and skeletal systems
   b. Functions of the dentofacial milieu: speech, deglutition, and mastication
2. Modification of the Dentofacial Complex
   a. Restorative modification of the oral cavity
   b. Modification of oral-facial function during speech
   c. Psychosocial development and modification
3. Assessment: Selected Topics
   a. Oral sensation and perception
   b. Aerodynamic measurements and ultrasound techniques
   c. Acoustic and analogue studies
   d. Radiographic techniques
   e. Fiberoptics and Electromyographic techniques
   f. Articulation assessment

The planning committee selected as participants 20 individuals actively engaged in research in both dentistry and speech pathology. Acceptance to the workshop was based on the individual's willingness to write a manuscript on an assigned topic, from the outline. In the charge to the participants the committee described the proposed manuscript as follows:

> [It] . . . should critically evaluate past and current research that has been and is being done, and should deal thoroughly with profitable areas for future research. It is essential that this review be sufficiently comprehensive to cover the important research that has been done. . . . This statement should emphasize the basic clinical and research findings of the past, the working assumptions of today, and predictions of the directions for necessary, fruitful future activity. The review should emphasize gaps, voids, and contradictions in the literature as well as positive findings. The committee particularly urges you to emphasize in your presentation those materials which are sharply relevant to both dentistry and speech pathology.

Two three-day meetings were scheduled for early 1970 in New Orleans, Louisiana. Each participant was to bring a draft of his assigned paper to the first meeting, at which he was allowed 15 minutes to present highlights of his paper. After this presentation the meeting was opened for 15 minutes of group discussion. The conferees were instructed to discuss information which may have been omitted, errors in fact, or interpretation of the facts, that were presented, and reactions to the authors' speculations about profitable areas for future research.

At the close of the first three-day session the authors were instructed to evaluate the comments and to revise their papers accordingly. One week before the second three-day session, they were to send the revised manuscripts to two other conferees, who were to prepare a formal written critique of the papers, which would be presented again at the second three-day session.

The planning committee approved the plan calling for the critique, but chose not to include these criticisms in the published proceedings of the workshop. Each author was allowed to respond to the criticisms as he saw fit. The committee recognized that, under this plan, those who were asked to write the critiques might not take the assignment seriously and that the authors might choose to ignore constructive criticisms. However, the planning committee felt such reactions were unlikely in view of the serious, dedicated way in which the participants responded to their respective assignments.

The planning committee realized that the preparation of a critique was not necessarily a pleasant assignment, but felt that this, too, was a necessary phase in any disciplined work to be undertaken by a group of individuals representing such diverse background and orientation. Since the committee hoped to develop an authoritative and somewhat eclectic view of the general topic under investigation, some element of consensus was considered necessary. The planning committee chose this method as being superior to arriving at some kind of formal vote on consensus or to publishing the specific criticisms of any given paper.

In this context the committee proposed that the persons writing the critiques consider the following elements:

1. Has the significant literature been covered, including ongoing work?
2. Are there points that are unclear?
3. Is more illustrative material needed?
4. Have issues been overlooked or avoided?
5. Have needs for future research or possible profitable directions for future research been overlooked?
6. Is the level of presentation too abstract or too elementary for the audience?

During the second three-day meeting each author was given 10 minutes to highlight significant changes made in his second draft, after which each of the two individuals who had provided the formal written critique had 10 minutes to present criticisms. Then there was a 10-minute group discussion of the paper.

At the end of the second three-day meeting the authors again were given the opportunity to change their manuscripts, as they saw fit, relative to the critiques and the group discussion. Then the manuscripts were forwarded to the National Office of the American Speech and Hearing Association, where they were prepared for publication.

The planning committee realizes that in attempting a state-of-the-art document there undoubtedly will be areas of mutual interest which have been omitted or slighted. More than likely, some of these omissions result from the planning committee's failure to incorporate certain broad areas within the outline of the workshop. Also, omissions may occur as a result of the individual author's selective evaluation of the available literature. The readers of this manuscript are urged to consider these limitations in their appraisal. Undoubtedly, however, this document will provide a relatively current, fairly complete, and rather thorough examination of the state of our knowledge concerning the relationships between speech and the dentofacial complex.

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NEUROANATOMY OF SPEECH

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Speech is a complex process requiring the integrated activity of large portions of the nervous and muscular systems. In the cerebral cortex the speech activity is organized with outflow in the corticobulbar and corticospinal tracts to the major muscles involved in producing speech. There is a sensory flow back to the central nervous system, probably indicating the position of all of the structures related to speech, allowing other centers as the cerebellum to project the necessary impulses for a smooth flow of motor activity. Speech also is modified by hearing the spoken words, matching the output to that which is desired. The neuronal circuitry, as far as is known currently, will be reviewed in this section.

There are certain problems basic to the study of the neuroanatomy of speech. Since experimental animals are used in most neuroanatomical work, the exact analogy of their neuroanatomy to that of humans for this function is difficult to make, for although animals vocalize, they do not speak. In this discussion the animals used in reaching conclusions for different neural circuits will be mentioned, so that some reservation may be made for this system in man.

A number of different techniques have been used in the study of neuroanatomy of speech. Gross examinations of the brain and peripheral nervous system have shown the peripheral muscles and nerves utilized in speech. The remaining techniques can be divided into three types. (1) Ganglion cell reaction follows injury of the peripheral nerve. This neuronal reaction is used to determine the neuron of origin for a specific nerve. (2) Axonal and myelin degeneration occur after the peripheral axis cylinder has been severed from its cell body. The Marchi technique for degenerating myelin and the more recent Nauta method for degenerating axis cylinders are used to trace these fibers to their destinations. (3) Electrical or strychnine stimulation may be applied to neurons or to a tract, and the tract course and termination determined by recording from other parts of the brain or by noting functional effects of the stimulation as muscle movements.

In this paper we will review first the efferent system innervating the musculature producing speech. Then afferent input to the nervous system related to speech will be discussed.

Speech utilizes muscles moving the tongue, lips, palate, vocal cords, intercostal muscles, and diaphragm. The innervation of these muscles is from several different centers, all of which must be coordinated. The highest coordinating center for speech is in the cerebral cortex.

The precentral gyrus is the most posterior portion of the frontal lobe and lies in front of the central sulcus (Figure 1). The primary motor cortex, in the precentral gyrus, is a major source of fibers to the motor neurons innervating muscles. The lower portion of the precentral gyrus is involved directly in speech. The six-layered pattern of the neocortex is modified slightly in the motor cortex, with an increase of pyramidal cells in Layers III and V, and giant Betz pyramidal cells in Layer V.

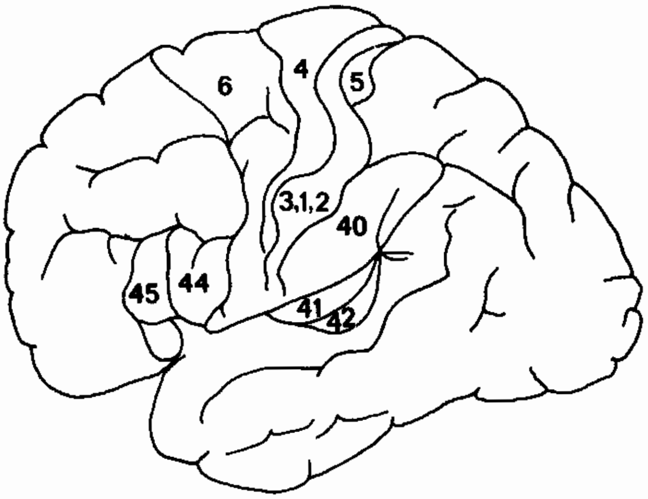

FIGURE 1. Cytoarchectonic areas of the cerebral cortex according to Brodmann. There are association connections between the primary auditory cortex (areas 41, 42) and Broca's area (areas 44 and adjacent portion of area 45), between Broca's area and the precentral gyrus (area 4), and between the precentral and postcentral gyri (areas 3, 1, 2).

Organization

There are many studies on the functional organization of the motor cortex in man and animals. The exposed cortex of man, stimulated by neurosurgeons, shows a reasonably clear pattern of organization, similar to that found in the sensory cortex. The region devoted to face and mouth activities occupies almost the lower one-third of the gyrus and includes innervation of the face, lips, jaw, and tongue, from above downward (Figure 2). Vocalization on electrical stimulation has been obtained between the lip and tongue areas (Penfield and Rasmussen, 1950).

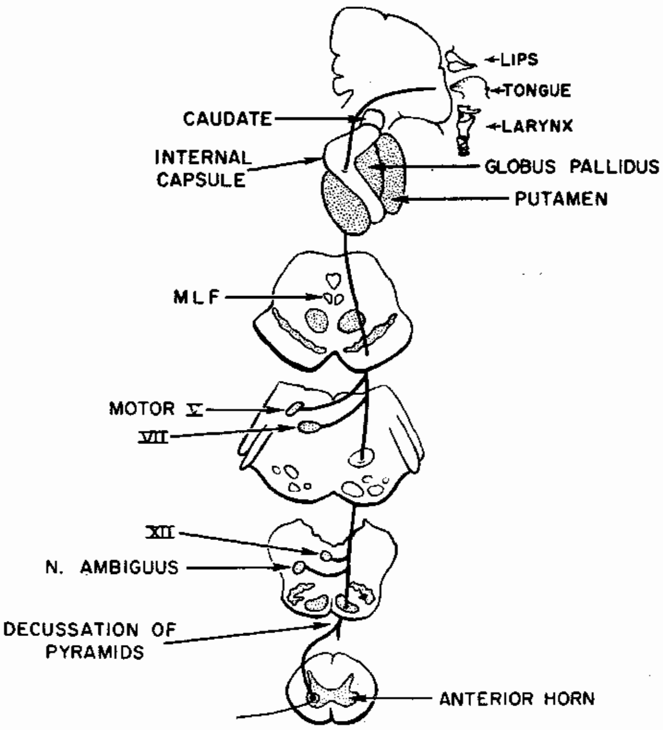

FIGURE 2. Diagram showing the path of nerve fibers from the lower precentral gyrus through the genu of the internal capsule to motor nuclei involved in speech. MLF = medial longitudinal fasciculus.

Connections

This motor cortex has intercortical connections with other parts of the cortex, and subcortical connections with the basal ganglia, diencephalon, brain stem, and spinal cord.

Intercortical Connections. There are abundant association fibers connecting the postcentral sensory to the precentral motor cortex, demonstrated by Milch (1932) in the monkey.

Auditory input is necessary to develop speech, and is necessary to maintain accurate speech. The only known level of interaction of the hearing and speech systems is in the cerebral cortex. Auditory input enters the central nervous system via the auditory nerve, which ends in the cochlear nuclei. From the cochlear nuclei, fibers ascend within the lateral lemniscus; most of these fibers end in the inferior colliculi. Fibers from the colliculi project to the thalamic relay, the medial geniculate body. Hence fibers continue to the auditory cortex in the transverse temporal gyri of the superior temporal gyrus. Lockard (1948) found numerous association fibers between the auditory association cortex and the motor cortex in the monkey. Thus it seems that the influence of auditory input on speech takes place in the cortex, probably via these subcortical association fibers.

By way of the corpus callosum the motor area connects to its contralateral part. Using strychnine neuronography in the monkey, McCulloch (1949) described projections from areas adjacent to the precentral and postcentral gyri to the ipsilateral and contralateral precentral gyri.

Subcortical Connections. Fibers from the precentral gyrus also enter into a recurrent circuit with the basal ganglia and thalamus. The first part of the arc courses from the motor cortex to the caudate nucleus. From this nucleus a second relay goes to the putamen, then to the globus pallidus. The next relay is to the ventral anterior nucleus of the thalamus (Hassler, 1949). This nucleus then projects to the motor and premotor cerebral cortex, as shown by Freeman and Watts (1947) in four cases of prefrontal lobotomy. The basal portions of this nucleus project to Broca's area.

Although fibers from motor cortex course to the zona incerta and substantia nigra, the major pathway from the precentral gyrus is the corticobulbar and corticospinal tracts projecting to the brain-stem nuclei and to the motor cells of the spinal cord. Kuypers (1958a), using the Nauta stain, studied four human brains with infarcts involving the precentral and postcentral gyri. He did not describe the exact extent of the lesions, although the motor speech cortex apparently was involved. He found degenerating fibers ending on ipsilateral nuclei pontis. Fibers also ended on the trigeminal motor, facial, and hypoglossal nuclei. More precise lesions were placed in the cortex of monkeys and chimpanzees (Kuypers, 1958b). Fibers to the motor nuclei originated in the face area of the precentral gyrus.

Sousa-Pinto (1970) studied projections from the primary motor cortex of cats on the perihypoglossal nuclei using the Nauta technique. He found that most of the cortical fibers to the perihypoglossal nuclei came from the face region of the first somatomotor cortex. It is likely that these nuclei are concerned with motor functions of the tongue.

THE HYPOGLOSSAL NUCLEUS

The hypoglossal nucleus, located in the caudal portion of the floor of the IVth ventricle, measures about 8 to 10 mm in length (Olszewski and Baxter, 1954) and is composed of large motor neurons with conspicuous Nissl substance. Fibers from this nucleus course ventrally through the reticular formation of the medulla to emerge between the inferior olivary eminence and the pyramid at the base of the medulla. It exits through the hypoglossal canal in the occipital bone just lateral to the foramen magnum. The nerve innervates the tongue musculature.

Organization

There are about 8000 neurons in the hypoglossal nucleus in man (Tomash and Etemadi, 1962). Pearson (1939) found that in 25-mm human embryos the hypoglossal nucleus was a prolongation of the cervical anterior motor columns into the medulla. Later the hypoglossal nucleus moved to its subependymal locale on either side of the median raphe. The hypoglossal nucleus can be divided into four subgroups. Based on central chromatolysis after cutting specific nerves to tongue muscles of dogs, Barnard (1940) concluded that the (1) ventrolateral nucleus innervates the genioglossal, transverse and vertical muscles; the (2) ventral nucleus innervates the geniohyoid muscle; the (3) dorsolateral nucleus innervates part of the infrahyoid musculature, the hypoglossal, and styloglossal muscles; and the (4) dorsomedial nucleus innervates the styloglossal muscle. Whether this organization applies to primates is not known.

Connections

Afferent Connections. The major input of fibers to the hypoglossal nucleus is from the precentral gyrus (Kuypers, 1958a). Most of the fibers are crossed.

Association Connections. The hypoglossal nucleus is connected to other brainstem nuclei via the medial longitudinal fasciculus. Thus fibers from the nucleus ambiguus connect to the contralateral hypoglossal nucleus, probably for coordination in speech and swallowing. There are also connections to the adjacent parahypoglossal nucleus, which itself projects to the cerebellum in the cat (Torvik and Brodal, 1954).

THE NUCLEUS AMBIGUUS

The nucleus ambiguus, supplying visceromotor fibers to the IXth and Xth cranial nerves, is the major motor nucleus for pharyngeal and laryngeal muscles. The nucleus is about 16 mm long, extending from the caudal portion of the inferior olivary nucleus rostrally. From it fibers course first dorsally and medially, and then turn laterally in the medulla to join the glossopharyngeal, vagus, and bulbar accessory nerves.

Organization

In the nucleus ambiguus in man there are about 1900 neurons (Tomasch and Ebenessajjade, 1961). Most neurons are large and multipolar with large Nissl granules. In the caudal part of the nucleus, cell groups become smaller and irregular in shape (Olszewski and Baxter, 1954).

The somatotopic arrangement of the nucleus ambiguus has been studied in several species. Szentagothai (1943), after placing lesions in the nucleus and studying motor end-plate degeneration in cats, concluded that the following muscles were innervated from the rostral to the caudal portions of the nucleus: (1) the cricothyroid muscle, (2) the cricoarytenoid dorsalis, (3) the thyroarytenoid, and (4) the lateral cricoarytenoid and arytenoid. Using monkeys, Furstenberg and Magielski (1955) studied activity after stimulation of the nucleus, and retrograde degeneration subsequent to motor nerve lesions. They concluded that the rostral part of the nucleus innervated the cricothyroid and cricoarytenoid, the midportion innervated abductors of the vocal cord, and the most caudal portion innervated abductors of the cords.

Connections

Afferent Connections. Several tracts send fibers to the nucleus ambiguus. Fibers from the corticobulbar tracts, arising from the face area, course through the genu of the internal capsule and terminate bilaterally on the nucleus ambiguus. From the main corticobulbar tract in the pons small aberrant bundles branch off to join the medial lemniscus. There they descend into the medulla to end in the nucleus ambiguus (Crosby, Humphrey, and Lauer, 1962). Other fibers from the crossed rubrobulbar tract innervate this nucleus, as Carpenter and Pines (1957) demonstrated in the monkey. These fibers probably furnish cerebellar input for coordination.

Association Connections. The medial longitudinal fasciculus carries fibers that interconnect many cranial nerve nuclei, including the nucleus ambiguus and the contralateral nucleus of the XIIth nerve. This connection possibly subserves coordination in speech and swallowing.

THE FACIAL NUCLEUS

The facial nucleus is the major structure innervating facial musculature. It is responsible for lip and cheek movements and thus is important in speech. The nucleus of the VIIth nerve is in the ventral tegmentum of the caudal pons. It is about 4 mm long and extends from the pontomedullary junction rostrally to the level of the abducens nucleus. There are about 7000 neurons in this nucleus in man (Van Buskirk, 1945).

Fibers from the facial nucleus course dorsally and rostrally to curve around the VIth-nerve nucleus in the floor of the IVth ventricle. They then course caudally, ventrally, and laterally to emerge from the brain stem at the pontomedullary junction, just rostral to the fibers of the VIIIth nerve. The facial nerve continues in the facial canal through the temporal bone to emerge at the stylomastoid foramen. It then branches to innervate the facial muscles.

Organization

The facial nucleus is composed of large multipolar motor neurons, which tend to form several groups. Based on embryological studies on the human fetus, Pearson (1946) divided the VIIth nucleus into six groups of cells: (1) dorsal, (2) intermediate, (3) medial, (4) ventral, (5) ventromedial, and (6) a ventrolateral group. Courville (1966a) studied the facial nucleus using the technique of retrograde chromatolysis in newborn kittens. He concluded that the platysma, which may help to lower the jaw during speech, was innervated by the ventromedial group, and that the ramus buccolabialis superior and ramus buccolabialis inferior were innervated by the lateral group. In dogs and cats the medial group is prominent, probably related to the auricular musculature, while in man the lateral group is prominent, possibly related to the development of fine lip movements.

Connections

Afferent Connections. In experimental animals and in man fibers originating from the motor cortex course to the facial nucleus (Kuypers, 1958a,b). A relatively large region of the lower portion of the precentral gyrus is devoted to lip movement (Penfield and Rasmussen, 1950). Some corticobulbar fibers to the nucleus of the VIIth nerve leave as the pontobulbar aberrant pyramidal tract, and travel in the medial lemniscus to the VIIth nucleus. The organization of projections onto the facial nucleus is not known.

Courville (1966b) produced lesions in the red nucleus in cats and studied axonal degeneration using the Nauta and Glees techniques. He found that the red nucleus projected to the dorsomedial and intermediate groups of the contralateral facial nucleus. Thus there was no input to that portion subserving lip movement in the cat.

Association Connections. In the medial longitudinal fasciculus there are interconnections between the motor nuclei of the Vth and VIIth nerves, probably subserving both speech and chewing.

MOTOR NUCLEUS OF THE VTH NERVE

The motor nucleus of the Vth nerve, via the mandibular nerve, serves the muscles of mastication, that is, the temporalis, masseter, and medial pterygoid muscles. It functions in speech by closing the jaw. This ovoid nucleus is in the midportion of the pontine tegmentum. It extends for a distance of about 4 mm, ending at the level where the locus caeruleus first appears. The neurons are large multipolar ganglion cells with coarse Nissl substance, similar to those found in the anterior motor horns.

From this nucleus course fibers which leave the pons as the portio minor, join the mandibular nerve, and supply the masseter, temporalis, and internal and external pterygoid muscles. Motor fibers are given also to the tensor palati, mylohyoid, and anterior belly of the digastric muscle.

Organization

From studying lesions of this nucleus in cats, Szentagothai (1949) concluded that the temporalis and masseter muscles were innervated respectively by the medial and central parts of the nucleus. We have no data concerning organization of this nucleus in primates or man.

Connections

Afferent Connections. Corticobulbar fibers from the lower part of the precentral gyrus pass via the genu of the internal capsule to the contralateral trigeminal motor nucleus. A major pontine aberrant pyramidal tract innervates this nucleus (Crosby, Humphrey, and Lauer, 1962). These corticobulbar fibers, along with the crossed rubrobulbar fibers (Carpenter and Pines, 1957), probably furnish the major input to this nucleus for speech.

ANTERIOR MOTOR HORN CELLS, RESPIRATION, AND SPEECH

During speech, respiration must stop and a smooth, forceful expiration must occur. Although the motor and sensory innervation of the lungs and thoracic musculature is well known, little is known about the anatomical connections responsible for respiration in higher regulating centers. Most of our present knowledge is based on electrical stimulation of parts of the brain stem and cerebral cortex. In man cessation of respiration has been produced by stimulation of a small area in the rostral precentral cortex (Bucy and Case, 1936). One might speculate that fibers from Broca's area project to this region of the cortex related to respiration, for integrating respiration with speech.

It is possible that the cerebellum also may coordinate these activities. Cerebellar disorders, such as olivopontocerebellar degeneration, produce abnormal speech, possibly caused by poorly coordinated thoracic musculature involved in producing the necessary smooth flow of air through the larynx.

CEREBELLUM AND SPEECH

Neurologists and speech clinicians know that patients with cerebellar disorders have speech problems. The typical scanning, or poorly coordinated, speech can even indicate that the cerebellum or some of its connections are at fault.

Afferent Connections

Torvik and Brodal (1954) studied the perihypoglossal nuclei connections to the cerebellum by creating lesions in different parts of the cerebellum in young cats, and killing the animals about one week later. Noting neuronal reaction in the perihypoglossal nuclei, they outlined projections of the nucleus intercalatus, nucleus praepositus hypoglossi, and nucleus of Roller to the cerebellum. The perihypoglossal nuclei projected to the anterior lobe, the pyramis and uvula, and to the nucleus fastigii of the cerebellum. The authors suggested that these perihypoglossal nuclei are primarily related to motor functions of the tongue. It is possible that they receive collaterals from the hypoglossal nuclei, so that the cerebellum may anticipate activities the tongue is making.

By delivering shocks to the superior laryngeal nerve in cats and recording from the cerebellum, Lam and Ogura (1952) were able to identify the areas of the cerebellum activated by sensory input from the larynx. They found bilateral evoked cerebellar potentials in the paramedian lobule and in the ansiform lobule of the cerebellum. These cerebellar areas may be important in the preservation of tonus in the vocal cords and coordination or maintenance of smooth speech.

Efferent Fibers

The major output of the cerebellum is from the cerebellar cortex to the basal cerebellar nuclei. From these nuclei, fibers course into the brain stem, primarily to the red nucleus and to the ventral thalamus. It is interesting that fibers from the fastigial nucleus, one of the areas receiving input from the parahypoglossal nuclei, project to the solitary nucleus, as demonstrated in the rat by Achenbach and Goodman (1968). This suggests the possibility that the cerebellum may modify sensory input to the nucleus solitarius from the periphery.

THE SENSORY SYSTEM FOR SPEECH

An elaborate sensory system of touch, pressure, and stretch receptors furnishes a continual flow of impulses to the nervous system indicating the position and activity of muscles and surfaces. Lesions of the sensory system may result in abnormalities in speech, verifying the importance of this information in developing and maintaining normal articulation. The significance and mechanisms of oral sensation in speech are reviewed by Ringel elsewhere in this *Report*. The neuroanatomical basis of sensory input from the other areas related to speech will be reviewed in this section.

DORSAL ROOT GANGLIA

Much controversy has centered about whether there are afferent fibers in the hypoglossal nerve. The best evidence at present is that afferents from the tongue enter the central nervous system via upper cervical dorsal root ganglia. Egel, Bowman, and Combs (1968) studied the axonal diameters of fibers in the lingual and hypoglossal nerves in the rhesus monkey. They concluded that the proximal part of the hypoglossal nerve did not contain enough large fibers to suggest that it had muscle spindle afferents. However, distal to the connection of the hypoglossal nerve to the cervical roots, there was an increased proportion of large-diameter fibers, suggesting that lingual nerve spindle afferents are present in the distal hypoglossal nerve. Their course was shown by Bowman and Combs (1969a) in rhesus monkeys. The authors stimulated the distal hypoglossal nerve and recorded potentials in the contralateral cerebral cortex. Sectioning the second or third cervical dorsal roots on the same side as the stimulation caused the evoked cortical response to disappear. They concluded that these afferents coursed via the ipsilateral dorsal roots. From the spinal cord, fibers conducted impulses to the contralateral ventral posteromedial nucleus of the thalamus (Bowman and Combs, 1969b), with projections then to the lingual sensorimotor areas in the postcentral and precentral gyri (Bowman and Combs, 1969c).

THE TRACTUS SOLITARIUS

Sensory fibers from cranial nerves VII, IX, and X form the fasciculus solitarius and terminate in the nucleus solitarius. This nucleus is important in receiving sensory information from the pharynx and larynx to aid in the coordination of speech.

The nucleus appears in the caudal medulla and extends rostrally to the caudal pole of the facial nucleus, a distance of about 16 mm. The nucleus lies lateral to the dorsal motor nucleus of the vagus and medial to the nucleus gracilis. Within and surrounded by the nucleus solitarius is the tractus solitarius. The tractus decreases in size as it courses caudally.

Organization

Olszewski and Baxter (1954) divided the nucleus of the tractus solitarius into three subgroups. One part, the dorsal sensory nucleus of the vagus, is dorsal to the tractus. Another part surrounds the tractus solitarius and is the ventral sensory nucleus of the vagus. At the level of the area postrema is the third part, the subnucleus gelatinosus.

Connections

The solitary nucleus is more than a relay nucleus for sensory input to the central nervous system. It appears to integrate input from many sources and influence many areas. It is affected by input from the primary sensory receptors in the tongue and pharynx, as well as from the cerebral cortex and from the spinal cord. Its output is to the cortex as well as to the spinal cord.

Afferent Connections. Torvik (1956) studied cranial nerve input to the nucleus solitarius in the rat. He created lesions in the cranial nerves and found that afferent fibers from cranial nerves VII, V, IX, and X terminated on the nucleus of the solitary tract successively in this rostrocaudal order. Kerr (1961) studied the relationship of the trigeminal nerve to the nucleus solitarius by performing trigeminal rhizotomies on cats. He found that a contingent of fibers from the Vth nerve ended on the dorsomedial parts of the upper third of the solitary nucleus. The specific origin of these fibers was not described.

Thus it appears that afferent impulses come to the nucleus solitarius from the sensory nerves of oropharynx, larynx, and possibly from a portion of the face.

Brodal, Szabo, and Torvik (1956) created lesions of the cortex in a series of cats and studied the pattern of degenerating axons demonstrated by the Glees method of silver impregnation. They found that fibers from widespread (but particularly the frontoparietal) regions of the cortex coursed to the nucleus of the solitary tract. This suggests that the cerebral cortex has some influence on afferent activity from the face and oropharynx.

Central Connections. Allen (1923) studied the nucleus solitarius in the guinea pig by producing lesions in this structure and following the pattern of degeneration using the Marchi technique. He found that fibers from the caudal part of the nucleus ascended in the opposite medial lemniscus to the thalamus. Fibers from the more rostral nucleus solitarius ascended in the opposite medial lemniscus and also in the restiform body into the caudal cerebellar cortex. Their course was similar to that of the dorsal spinocerebellar tract, suggesting that they are muscle sense fibers for the cerebellum.

THE TRIGEMINAL COMPLEX

The trigeminal complex comprises a group of nuclei in the pons and medulla, concerned mostly with facial sensation but including a motor nucleus discussed earlier. These nuclei, involved with mouth and lip position, sensation and tone, are important in the speech process. The sensory nuclei are the trigeminal ganglion, the main sensory nucleus, the spinal nucleus, the nucleus supratrigeminalis, and the mesencephalic nucleus of the Vth nerve.

Organization of Fibers from the Trigeminal Nerve

Darian-Smith, Mutton, and Proctor (1965) studied receptor fields in the trigeminal ganglion of cats. They found that stimulation in the mandibular skin field activated neurons in the most lateral portions of the ganglion, adjacent to the mandibular nerve. In the squirrel monkey Lende and Poulos (1970) stimulated the tongue, teeth, and jaw, and recorded with microelectrodes neuronal activity in the third division of the trigeminal ganglion. They found neural responses to thermal and tactile stimulation of the tongue intermingled in the same region, and concluded that there was no organization according to modality of stimulation in the ganglion.

In the trigeminal complex some organization was found by Kruger and Michel (1962), who studied receptor fields in the trigeminal complex in cats. By stimulating the buccal cavity and tongue they produced cell activity in the medial part of the sensory V complex with the mandibular division dorsal to the maxillary. Each part of the periphery was represented on a rostral caudal line of cells from the main sensory nucleus to the spinal cord. Kerr (1963) studied the brain stem of the cat and monkey after cutting each of the three divisions of the trigeminal ganglion. Nauta staining showed a clear lamination of fibers in the main sensory nucleus, the sensory root, and the spinal tract of the Vth nerve. The mandibular division fibers occupied the dorsomedial parts of the trigeminal nucleus, the maxillary division occupied the midparts of the nucleus, and the ophthalmic division was most lateral and ventral. A contingent of fibers passed to the solitary nucleus from the mandibular division. In a study of the receptor fields from physiological facial sensation in monkeys, Kerr et al. (1968) confirmed their findings in the cat, that there is a rostrally caudally oriented column of cells, with the mandibular column most medial in locale. If the organization is similar in man, the medial portion of this nucleus would be involved in speech.

Main Sensory Nucleus of the Vth Nerve

The main sensory nucleus has a considerable projection from the mandibular division of the trigeminal nerve. Dubner (1967) studied the responses to various stimuli of single neurons in the main sensory nucleus in cats. All cells had restricted excitatory fields and were activiated by non-noxious stimuli as hair movement, light touch, or pressure on the mouth or face. Cells responding to oral-facial stimulation were in the lateral part of the nucleus.

Nucleus Supratrigeminalis

The nucleus supratrigeminalis is dorsal to the main sensory nucleus. It is composed of neurons with elongated cell bodies, distinguishing it from the rounded neurons in the sensory nucleus. It is the only trigeminal nucleus known to receive direct connections from higher levels (Torvik, 1956). Jerge (1963a), recording electrical activity of neurons in this nucleus in cats, found that units responded to movements of the mandible and pressure on oral structures. He divided neurons into three types: (1) those activated by pressure on teeth, gingiva, palate, and tongue; (2) those activated by jaw-opening movements; and (3) those inhibited by jaw opening. This nucleus is probably active in jaw reflexes and in jaw movements in speech, for it is located near the mesencephalic, main sensory, and motor nuclei of the Vth nerve.

Mesencephalic Nucleus of the Vth Nerve

This nucleus, lateral to the fourth ventricle in the rostral pontine tegmentum, is the only known sensory nucleus in which primary ganglion cells are in the central nervous system. The neurons are large, appearing in small groups.

Neurons. The fibers of these neurons exit from the pons with the Vth nerve, entering the motor and sensory divisions. They conduct proprioceptive sensation from the muscles of mastication, teeth, and hard palate. Jerge (1963b) studied the neurons in the mesencephalic nucleus in cats, stimulating the face and teeth and recording from single units in this nucleus. He found two types of neurons in the nucleus: (1) those innervating muscle spindles of the masseter, temporalis, and medial pterygoid muscles; (2) those innervating dental pressure receptors in teeth. In the cat, Corbin and Harrison (1940) also found action potentials in this nucleus to blunt pressure on the hard palate. There was no activity of these neurons with tongue or facial movement. Thus these neurons are probably active in jaw movements during chewing and speech.

Association Connections. Smith, Marcarian, and Niemer (1968), by stimulating the mesencephalic nucleus and its nerves in cats, found neurons projecting to the ipsilateral and other neurons projecting to the contralateral motor-V nucleus. Pearson (1949) found that, in the opossum, fibers project to the cerebellar hemispheres and vermis, as well as to the Vth nerve and some other structures.

Projections from the Trigeminal Complex

Much work has been done tracing projections from the trigeminal complex to the thalamus. Walker (1939), studying the secondary degeneration after lesions of the trigeminal nuclei in monkeys, found that fibers from the spinal trigeminal nucleus crossed the midline and ran between the inferior olive and pyramid. In the pons these fibers moved to the lateral margin of the medial lemniscus, terminating on the medial part of the nucleus ventralis posterior. From the main sensory nucleus two groups of fibers arose. One crossed the midline and followed the medial lemniscus lying on its dorsal medial surface, and ending in the ventral posterior medial thalamic nucleus. The second group of fibers passed through the dorsolateral part of the reticular substance. Although a few fibers were crossed, the majority were uncrossed. Most ended in the medial part of the nucleus ventralis posteromedialis. Similar findings were obtained by Carpenter (1957) in the rhesus monkey. Eisenman et al. (1964), studying the cat, found that secondary touch cells with small oral receptive fields located in the dorsomedial part of the main sensory nucleus sent their axons into the ipsilateral dorsal ascending trigeminal tract.

Electrophysiological studies in cats have shown a rich contribution from the trigeminal complex to pontine reticular formation (Langlois and Lamarche, 1962).

Thus it seems that the main sensory nucleus transmits fine tactile stimuli via an ipsilateral and a contralateral secondary ascending tract of the Vth nerve to the arcuate nucleus of the thalamus. Fibers from the spinal nucleus of the Vth nerve ascend as a contralateral ventral secondary ascending tract of the nerve to end also in the arcuate nucleus. A contribution of the trigeminal complex also appears in the reticular formation.

THALAMUS

Different nuclei in the thalamus serve as the final relay for all sensory input. The ventral posterior medial nucleus is that relay for facial sensation.

Afferent Connections

In the macaque monkey, Mountcastle and Henneman (1952) mapped areas of the thalamus responsive to physiological stimulation of the body. They found representation of the contralateral face in the lateral parts of the arcuate nucleus, with lips, intraoral structures, and larynx represented medially, in that order.

Central Connections

Projections to and from the postcentral gyrus have been demonstrated. Walker (1938) produced lesions in the postcentral gyrus in chimpanzees and monkeys, and studied the resultant retrograde neuronal degeneration in the thalamus. He concluded that the arcuate nucleus projects to the face area in the postcentral gyrus.

To demonstrate subcortical projections from the postcentral gyrus, Krieg (1954) ablated postcentral cortex in monkeys and traced tracts using the Marchi technique for degenerating myelin. He found that fibers from the face area projected to the lateral arcuate nucleus of the thalamus. Apparently, activity in the sensory cortex has some influence on sensory neurons in the thalamus.

SENSORY CORTEX AND SPEECH

The sensory cortex in man is in the postcentral gyrus. The postcentral gyrus differs from the precentral motor cortex in that it is moderately thinner, has better developed granule cell layers, and lacks the giant pyramidal cells of Betz. This cortex has a well-developed internal granule cell layer and is characterized also by the columnar arrangement of neurons.

Organization

The pattern of organization of the postcentral gyrus in man has been documented by electrical stimulation of the cortex (Penfield and Rasmussen, 1950). The lower one-third of the gyrus serves a sensory function for the face, lips, jaw, tongue, and pharynx. The lips and tongue take the greater part of this area.

Connections

Subcortical connections were discussed in the sections on dorsal root ganglia and thalamus.

Intercortical Connections. The sensory cortex is connected to other areas of the cortex by short intercortical connections. Connections to the adjacent motor cortex course by short fibers below the central fissure (Krieg, 1954). In the monkey, fibers from the auditory cortex project to adjacent association areas with relays then to the inferior postcentral gyrus (Lockard, 1948).

CONCLUSIONS

It is clear that, although much has been written about brain-stem structures in animals, little is known about these structures in man. Nevertheless it might be interesting to speculate on some of the neural mechanisms involved in speech, based on what we know about these neural structures and connections.

The integrative activity resulting in speech probably begins in the cerebral cortex with a concept which can be vocalized. Broca's area in the cortex may then be influenced to initiate the speech process. Projections from this cortical region go to the motor cortex. From here a major projection courses to the motor nuclei involved in speech, that is, the hypoglossal nucleus, the nucleus ambiguus, the facial nucleus, and the motor nucleus of the Vth nerve. At the same time, fibers from the cerebral cortex project to the basal ganglia, and to the cerebellar cortex via the pontis. These projections probably function to smooth and to create the necessary motor tonus for vocalization. Projections from Broca's area to the respiratory motor area may coordinate this activity with speech.

Neurons in the hypoglossal nucleus, nucleus ambiguus, facial nucleus, and motor nucleus of the Vth nerve are played upon by projections from the precentral gyrus and by the cerebellar cortex via the red nucleus. Also, shorter connections interconnect these nuclei with one another, possibly aiding in their coordinated activity. Fibers from these nuclei act upon the musculature of the tongue, larynx, mouth, and jaw to produce speech.

Sensory endings in the mucosa and musculature of the tongue, larynx, mouth, and jaw are activated by touch, pressure, and position. This information is fed into the dorsal horns of the spinal cord, the nucleus solitarius, and to the trigeminal sensory complex. These structures are also influenced by the cerebral cortex and reticular formation, possibly enhancing or dampening their activity, as the occasion demands. These sensory nuclei then project to the ventral posterior medial nucleus of the thalamus, and then to the postcentral gyrus of the cortex.

Auditory feedback of what is being said projects to the transverse temporal gyri. From these gyri there are projections to the motor cortex, allowing a comparison of the results of speech and possibly influencing the motor production of speech.

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MUSCULAR DEVELOPMENT AND MATURATION OF THE DENTOFACIAL COMPLEX: NORMAL AND ABNORMAL

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The musculature of the oral- or dentofacial complex may be divided into four groups on the basis of neural, functional, anatomical, and developmental differences. These muscle masses are highly interrelated and there may be considerable overlap in one or more of these four criteria for classification. The four muscle groups of the dentofacial complex include (1) the muscles of mastication, (2) the intrinsic and extrinsic muscles of the tongue, (3) the muscles associated with the soft palate, and (4) the muscles of facial expression, principally those of the lips and cheeks.

The muscles of the oral-facial complex of concern in this paper are classified as skeletal muscle. Skeletal muscle is voluntary, in contrast with involuntary smooth and cardiac muscle. However, although our attention may be focused on movements surrounding an individual muscle, the physiology of movement is such that the body "programs" movements in muscle groups. Generally, a skeletal muscle fiber is described as being 10 to 100 microns in diameter, length varying according to the length of the muscle involved; multinucleated, with the nuclei found just beneath the cell membrane or sarcolema; nonbranching and nonanastomosing; and displaying alternating light and dark cross-striations with less discrete longitudinal striations (Bowman, 1840; Walls, 1960; Bloom and Fawcett, 1962; Barnett, 1966).

Histological variations have been observed among skeletal muscle fibers found within the same muscle. As early as 1873, Ranvier (1873, 1874) declared that not all fibers found in skeletal muscle were the same. In his study of the rabbit, Ranvier observed two types of muscle fiber whose color difference could be distinguished by the naked eye. Ranvier referred to them as *red fibers* and *white fibers,* on the basis of their color. He attributed various individual histological characteristics to each type of fiber and demonstrated functional differences between the two fiber types. He showed that red fibers have a slower, more prolonged contraction in response to stimulation, compared to the faster reacting white fibers. Ranvier's observations created considerable controversy concerning the function and histology of muscle fibers.

Denny-Brown (1929) believed that the red pigmentation was not essential to the slower type of contraction and attributed it to some function other than contraction. Haggqvist and Lindberg (1962) studied muscle spindles in the rabbit and found that red muscles contained more spindles than did white fibers. Moreover, these spindles could be divided into those which would induce a rapid muscle response and those which would elicit a slower contraction. Those which induced rapid contraction were found in greater numbers in both red and white muscles. This type of spindle consistently made up about 64% of the spindles in white muscle. In red muscle, however, spindles inducing rapid contraction made up 55 to 85%. Haggqvist and Lindberg (1962) concluded that the differences in spindle prevalence in red fibers accounted for the difference in contraction rate observed by Ranvier, since they found that the particular muscle which Ranvier studied possessed the smallest percentage of fast muscle spindles.

Walls (1960), in a review of the histology of red and white fibers, concluded that the significance of color in muscle fiber type remains unspecified. To date, set characteristics unique to red fibers or to white fibers have not been established. Instead of being dichotomous, red and white muscle fibers present a continuum of variations. For example, Beckett (1962) found that red fibers in normal mammalian skeletal muscle were rich in dehydrogenases and lipids but poor in glycolytic enzymes and glycogen. In comparison, white fibers were rich in glycolytic enzymes and glycogen and poor in dehydrogenases and lipids. In addition, he found certain other fibers which possessed intermediate properties. It appears that in the majority of animals, including man, both fibers enter into the composition of all the muscles, with one or the other type of fiber predominating according to the type of muscle.

In general, skeletal musculature in man is derived from myotomes which in turn differentiate from somites. However, in the head and neck region certain muscle groups are derived from branchial arch mesoderm. The muscles of mastication and facial expression and those associated with the soft palate are all nonsomitic. The tongue, or lingual musculature, however, is still generating disagreement as to its embryonic origin.

THE MUSCULATURE

Facial Musculature

That portion of the facial musculature most intimately associated with the oral cavity is located in the lower third of the face, that is the lips and cheeks. Eisler (1912) gave a good definitive description of the arrangement of the facial musculature and its variations. The gross anatomy of the facial musculature can be obtained from any of a number of anatomy texts (*Quain's Elements of Anatomy,* 1923; *Cunningham's Anatomy,* 1964; *Cunningham's Manual of Practical Anatomy,* 1967; Gardner, Gray, and O'Rahilly, 1965; *Gray's Anatomy,* 1969). In addition to the expression of emotion, the human lip and cheek musculature participates in speech, deglutition, and mastication. The facial muscles are unique in that unlike most skeletal muscle they are inserted into the skin and mucosa by thin elastic tendons. Martone and Edwards (1962a) suggest that the facial muscles do not have fascial sheaths. This property, coupled with minute movements of very small muscle bundles, makes possible the preponderance of synchronistic movements that may be achieved independently from the rest of the muscle or within the complexity of muscle groups. Such movements may be observed during elaborate facial expression of such emotions as pain, sorrow, or happiness and during the function of the lower facial muscles in speech. Martone and Edwards (1962a) state that the lower facial musculature may be regarded as one muscle if the muscles of the lips are viewed as a whole instead of individually. The continuity of fibers between muscles elevating and depressing the lips gives the labial muscles the appearance of a single muscle mass arising from a fixed bone (the maxilla) and inserting into a movable bone (the mandible). Thus, lip musculature takes on the characteristic of most skeletal muscle: that of being connected to bone at both its origin and insertion. Martone and Edwards conclude that labial muscles may play a role in minute mandibular movements associated with the functions of speech and facial expression (Ulrich, 1959).

Developmentally the facial muscles arise in situ from branchial arch mesenchyme. Therefore, these muscles receive a special visceral motor innervation, the facial or seventh cranial nerve. Since the studies of Rabl (1887) and Gegenbaur (1890) the embryonic development of the facial muscles and nerve has been associated with the hyoid and second branchial arch. For nearly half a century Futamura's (1906) report on the morphogenesis of the human facial musculature was the most extensive in existence. He is widely quoted in the literature, including the textbooks of Keibel and Mall (1910), Quain (1923), Patten (1946), and Arey (1954). Later Huber (1931) charged that Futamura's work was "full of unreliable statements." He considered Popowsky's (1895) work far superior but unfortunately incomplete. Futamura believed that the levator palatine and muscular uvulae were derived from the mesenchyme of the hyoid arch. He also stated that there were primitive sphincter arrangements at an early age around the eye, nose, mouth, and ear, which, with the exception of the oral sphincter, disappeared and were replaced by new formations. Gasser (1965), who has carried out an excellent and detailed study of the embryology of the facial nerve and musculature in the human fetus, did not find those early sphincters, nor could he attribute the origin of the two mentioned palatal muscles to the second branchial arch.

At birth the facial muscles are extremely well developed compared to the rest of the body musculature. This is characteristic of the rest of the oral musculature as well, and in keeping with the cephalocaudal sequence of development of the human fetus. Lewis (1910) and Gasser (1965) found that facial premuscle masses are formed between the ages of eight and nine weeks, menstrual age. Gasser's study begins with an embryo of 4.25 mm crown-rump length at approximately six weeks, menstrual age. At 80 mm crown-rump length, or 14½ weeks of age, all of the facial muscles are present in their definitive positions.

Tongue Musculature

The tongue is covered by a mucous membrane and is a highly mobile organ capable of manifold fine movements. The body is made up of intrinsic and extrinsic muscle groups which are extensively interwoven. This makes a functional study of these muscles difficult. At present there are no adequate descriptions of the morphology of the tongue though a good one was given by Abd-el-Malek in 1939.

The intrinsic muscle group lies entirely within the substance of the tongue and possesses no bony attachments. There are four intrinsic lingual muscles and their names—superior and inferior longitudinal, vertical, and transverse—indicate the direction of their fibers. This group of muscles is responsible for shaping the tongue (Scott and Dixon, 1959; Kawamura, 1961; Scott and Symons, 1967). The extrinsic lingual muscles attach the tongue to various bony structure, for example, the hyoglossus to the hyoid bone, the styloglossus to the bony palate. Kawamura (1961) states that these muscles are responsible for the fast movements of protrusion, retraction, or lateral deviation. However, Bole and Lessler (1966) believe that protrusion of the tongue relies heavily on the activity of the intrinsic muscles and significant relaxation of the extrinsic muscles. They found that the genioglossus was active during protrusion and lateral movement but reached its greatest activity when the tongue met resistance. All of the muscles of the tongue, with the exception of the palatoglossus, are innervated by the hypoglossal or twelfth cranial nerve. The palatoglossus is innervated by the vagus or tenth cranial nerve. Accordingly, Arey (1954) and Martone and Edwards (1962a) believe that the palatoglossus muscle does not arise with the rest of the tongue musculature. Rather, they postulate that the palatoglossal muscle has its origin in the fourth branchial arch, since the vagus nerve is developmentally associated with this arch.

A definitive description of tongue development has not been advanced, and considerable controversy exists over the origin of the musculature. The covering of the tongue arises from the floor of the primitive pharynx, while phylogenetically at least, its muscular component apparently arises from occipital somites. Hunter (1935) and Hazelton (1969) demonstrated that the hypoglossal musculature of the chick arises from occipital somites and apparently, also, from the first two cervical somites. The innervation of the muscles of the tongue by the hypoglossal nerve seems to indicate that they arise from the upper somites, since embryologically this nerve is associated with the occipital region of the fetus. This would be with the exception of the first somite in man, which Arey (1938) has shown disappears without making any significant contribution to the human musculature. On the other hand, Lewis (1910) insisted that tongue muscles arise in situ from the mesenchyme in the floor of the primitive pharynx. Kingsbury (1915) disagreed with Lewis. He believed that these muscles were derived from the first three or four somites, but admitted that tracing the migration of the lingual muscle primordia in the human embryo is difficult. Bates (1948) studied the embryology of the hypoglossal musculature in the cat and declared that it arises from the first six somites (four occipital and the first two cervical).

Another controversy exists concerning the presence or absence of proprioceptive nerve endings in the muscles of the tongue. Hewer (1935), Carleton (1937), and Boyd (1937) were unable to locate such nerve endings in the lingual muscles. Langworthy (1924) and Cooper (1953) found muscle spindles in animal and human tongues respectively. Since the tongue is capable of carrying out a number of fine, skillful movements, Kawamura (1961) believed there must be proprioceptive information transmitted directly to the hypoglossal nucleus in the brain stem. It is generally thought today that if proprioceptive endings are present in the muscles of the tongue, they are probably sparse in distribution and confined to the extrinsic musculature.

Masticatory Musculature

The muscles of mastication serve as the primary movers of the mandible. There are four pairs of masticatory muscles: the temporalis, the masseter, the lateral pterygoid, and the medial pterygoid. The interaction of these muscles accounts for the complex movements of the mandible (Hickey, Stacy, and Rinear, 1957; Scott and Dixon, 1959; Woelfel et al., 1960; Basmajian, 1967).

With the exception of the lateral pterygoid, those muscles which depress the mandible generally are not classified as masticatory muscles. These depressors include the suprahyoid muscles and the digastric muscles. Hickey, Stacy, and Rinear (1957) found that both of these groups, along with the lateral pterygoid muscles, were active in uncontrolled opening. In fact, the digastric muscles showed their greatest activity during this movement.

The masticatory muscles have their origin in the mandibular portion of the first branchial arch (Lewis, 1910; Patten, 1946; Arey, 1954; Langman, 1963). The mandibular division of the trigeminal or fifth cranial nerve is associated with the mandibular arch and provides all of the masticatory muscles with their motor innervation. Unfortunately, the studies of the development of the human muscles of mastication are inadequate at this point. However, considerable investigations have been carried out on other mammals by such investigators as Edgeworth (1914, 1935).

Palatal Musculature

Another group of muscles closely associated with the tongue are those which act on the soft palate. Martone and Edwards (1962b) separate these muscles into two groups—intrinsic and extrinsic. The former group includes the tensor veli palatini, levator veli palatini, and musculus uvulae, while the latter includes the palatopharyngeus and palatoglossus. These muscles function in speech (Silverman, 1956; Martone and Edwards, 1962b; Shelton, Brooks, and Youngstrom, 1964) by depressing the palate for the production of nasal sounds and elevating it for all other sounds. Thus, the soft palate serves as one of the articulators of speech, just as the tongue, only its activity is primarily backward instead of forward.

The embryology of the muscles of the soft palate has not been studied extensively. All of these muscles, with the exception of the tensor veli palatini, arise from the fourth branchial arch (Patten, 1946; Arey, 1954; Barry, 1961). Lewis's (1910) findings disagree about the origin of the palatoglossus, which he believed arose from the third branchial arch. However, the vagus nerve, which innervates all of the muscles of the soft palate except for the tensor veli palatini, is associated embryologically with the fourth and fifth branchial arches. The tensor veli palatini arises from the mandibular arch along with the muscles of mastication and shares the same innervation (Lewis, 1910; Edgeworth, 1914; Patten, 1946; Arey, 1954).

Other Musculature

Two other muscles which should be considered as part of the oral musculature are the mylohyoid and geniohyoid muscles. They could be classified as the muscles of the floor of the mouth. The geniohyoid assists in depressing the mandible and receives its innervation from the first two cervical nerves, which, in turn, join and run with the hypoglossal nerve before innervating this muscle. The mylohyoid muscle elevates the tongue against the palate, thereby playing an important role in the first stages of swallowing. The mylohyoid is innervated by the mandibular division of the trigeminal nerve. Lewis (1910), Martone and Edwards (1962b), Edgeworth (1914), Patten (1946), and Arey (1954) agree that the mylohyoid muscle arises from the mandibular arch. The geniohyoid, by virtue of its spinal innervation, appears to have arisen from the first or second cervical somite.

FETAL REFLEXES

Considering the feeding abilities of an infant, in this case the human, all of the muscles under consideration are relatively well developed and capable of carrying out functions vital to life, for example, suckling and swallowing. For the newborn to carry on such activities, these muscles would have had to be functional in utero. Indeed, these responses have been demonstrated in the fetus at a very early age. Humphrey (1964, 1968a) has observed what she refers to as reflexes related to feeding which result from cutaneous stimulation of trigeminal sensory areas. These reflexes occur at about 8.5 weeks menstrual age. This is the earliest type of feeding-related reflex and is seen a week later than the avoiding type of reflexes, or flexion away from the stimulus.

Hooker (1939) found that the embryo first responds to cutaneous stimulation early in the eighth week menstrual age and observed spontaneous movement by 9.5 weeks. The initial development of fetal activity appears to be a total response pattern with specific reflexes being emancipated from the total response. Overt behavior appears to develop in a sequence which is unique for the animal in which it is observed (Hooker, 1936, 1944, 1960). Hooker (1938) demonstrated such development of the grasp reflex in the human.

Humphrey (1968a) also found this type of reflex development of the mouth-opening reflex. Windle (1944), on the other hand, believes that simple reflexes are the building blocks that are later integrated to form behavior.

A number of brief references in the literature concern observations of postnatal repetition of the same sequence of activity development seen in the fetus (Hooker, 1952, 1958; Humphrey, 1964). Humphrey (1970) studied this phenomenon and, in light of the evidence she presents, it does not seem likely that the swallowing reflex observed in the fetus is a learning process as Subtelny and Sukuda (1966) have speculated. Rather, the swallow reflex results from neural pathways becoming functional and allowing the response to occur.

Functionally, all of the oral-facial muscle groups are not only interrelated but dependent on one another to perform their tasks. Interruption in function of one muscle group will upset the balance and alter the activity of other muscle groups, which in turn must compensate for the loss in order for the system to continue its activities. If the function of all the muscles under discussion is learned (Silverman, 1956; Martone and Edwards, 1962b; Subtelny and Sukuda, 1966), with the exception of the postural reflexes of certain masticatory muscles which are considered to be antigravity muscles (Moyers, 1956; Basmajian, 1967), it is obvious that incorrect learning could account for some of the alterations in oral function and speech difficulties. However, if all oral activities are not learned, then it is likely that development of fetal activity out of sequence, or omission of a specific response, could result in speech defects or what we refer to as abnormal oral habits.[1]

MATURATION

The continuing development and maturation of the oral-facial musculature is an area where much study has been left undone. In addition, much of the literature we have is incomplete or fails to answer our questions. As an individual develops and matures, the oral muscles are believed to play a vital role in his continuing ontogeny. Those muscle groups most studied at this point are the perioral and lingual muscles. What has been of particular interest is the influence they exert on the developing jaws and teeth. Swinehart (1950) states that development of proper equilibrium of coordinating forces during the early stages of facial growth will allow the development of normal jaw dimension and occlusion. Brodie (1967) believes that tongue position and cheek and lip pressure guide erupting teeth into normal occlusion.

Stevens (1956), Winders, (1956), Kydd (1957), and Sims (1958) have found that in normal individuals the tongue exerts greater forces than the perioral musculature. Some investigators believe that alterations of these forces, such as seen in cases of tongue-thrust habit and sigmatism, result in abnormal growth (Subtelny and Sukuda, 1966; Winders, 1968). Likewise, growth patterns were found to be altered in cases where greater forces were exerted by the perioral muscles (Jacobs, 1967). In addition, in cases where there

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[1] Humphrey, T., personal communication (1970).

has been abnormal tongue posture, diminutive arch growth has been noted (Backlund, 1963). Eskew and Shepard (1949), Brodie (1967), and Swinehart (1950) found the same type of retarded arch development in cases of micro- and aglossia. In the other direction, Greene (1937) observed that alterations in growth of the skeletal system resulting in malalignment of the teeth impeded the motion and formations of the tongue. Obviously there is some sort of correlation between certain types of malocclusion and abnormal bone growth and the forces exerted by the encapsulating musculature. Just what this correlation is or its significance is not known. Jacobs and Brodie (1966) admit that the pattern and effect of intra- and extraoral forces and the constraints exerted by intraoral and perioral soft tissue upon skeletal bone, alveolar processes, and the dentition are not clearly understood. It appears, however, that either muscular forces are responsible for some cases of malocclusion or malocclusion in some cases causes abnormal forces to be exerted by lingual and perioral musculature or possibly both.

The adaptability of the oral-facial musculature to growth and development abnormalities is remarkable. Eskew and Shepard (1949) observed the potentialities of these muscles in a rare case of aglossia in a 22-year-old man. Although the patient had a noticeable speech impediment, he was still capable of verbal communication. Weinberg et al. (1969) reported a case of hypoglossia in a seven-year-old girl who compensated for the loss of a fully useful tongue by developing unique compensatory articulatory patterns.

Lesser examples of adaptability have been observed in masticatory function, which Silverman (1956) states is a process learned over a period of years. Moyers (1956) asserts that eccentric mandibular positions are learned as expedient mechanisms for avoiding occlusal disharmonies. Otherwise, malocclusion would cause the masticatory muscles to exert greater forces to overcome the occlusal discrepancies. Liebaman and Cosenza (1960) found that the pattern of electrical activity in the temporal and masseter muscles of individuals with malocclusions and normal occlusion could not be distinguished from one another. Nor did they find any difference between resting tonus and the type of occlusion. Hickey et al. (1959) carried out studies utilizing various occlusal schemes to determine what effect, if any, occlusion might have on muscular activity. They tested the external pterygoid and the temporal muscles. Within the individual subjects themselves, the recordings were relatively constant. He did note more variations between subjects.

CONGENITAL DISTURBANCES

Congenital malformations of the face and oral cavity are important developmental aspects of this region because of their interference with oral function and their displeasing esthetic effect. Naturally, since congenital defects are a form of abnormal development, they should be included in this paper. Of all the congenital malformations of the oral-facial complex the cleft is probably the most widely investigated, particularly the cleft palate and lip.

Normally, the palate is formed by the fusion of two lateral palatine shelves which appear during the sixth week of development as outgrowths of the deeper parts of the maxillary swellings (Langman, 1963). Initially, these palatine processes are growing down, with the tongue projecting up between them. The mechanism by which the tongue is withdrawn from between the palatine shelves is not understood, but it is generally attributed to growth changes. Humphrey (1968b, 1969) believes that repeated lowering of the mandible associated with the total reflex response seen in the human embryo at 8.5 weeks, menstrual age (Hooker, 1939, 1944; Humphrey, 1968a) pulls the tongue down from between the shelves. This action creates a lesser pressure in the primitive nasal cavities which causes the palatine shelves to be moved rapidly upward. After the palatine shelves achieve their horizontal position, the tongue and periodic intake of amniotic fluid exert pressure on the inferior surface of the palatine shelves, thereby maintaining their new position.

The etiology of cleft palate, as well as all other congenital defects of the oral cavity, may be genetic, environmental, or a combination of both. The purely genetic congenital malformations result from chromosomal aberrations or mutant genes. This accounts only for a minority of oral malformations. Those resulting from environmental influence alone are rare and the most easily preventable. Carter (1968) believes that the combination of both is the most common cause. Stern (1960) states that phenotype is potentially variable and is the result of interaction between the person's genetic makeup and his environment. Studies have been carried out to determine whether cleft lip and palate entities are separate, the same, or related, and just how they are transmitted. It has been fairly well established that cleft lip with cleft palate and cleft lip alone have a common genetic component, while cleft palate alone has a different entity (Woolf, Woolf, and Broadbent, 1963a; Witkop, MacCollum, and Rubin, 1967). Fukuhara (1965) believes that cleft lip with or without cleft palate is heritable dominantly rather than recessively, while Carter (1968) states that it is polygenic. Woolf, Woolf, and Broadbent (1963b) found the cleft lip and palate to be strongly heritable in some families through the action of a dominant single gene and less heritable in others through the interactions of polygenes and nongenetic factors.

If, indeed, Humphrey (1969) is correct and mouth opening reflexes are responsible for removing the tongue from between the developing palatal shelves, then an important nongenetic factor in cleft palates could be drugs taken by the mother. Thus, in early development of the embryo a critical period would exist when any agent that could influence the reflexes of the embryo would be a potential teratogenic agent in cleft palate. In addition, abnormal development of the embryo, that is, subnormal size or delayed muscular development, could affect palatal closure adversely.

The pathogenesis of cleft lip has been studied in A/J mice since this strain has been shown to be predisposed to cleft lip. These animals show a high incidence of spontaneous clefting with a frequency of occurrence of about 12%. Trasler (1968) concluded from his studies of the A/J mice that the cleft lip may be viewed as a threshold character or quasicontinuous variant. The classical theory of Dursy (1869) and His (1874, 1892) as cited by Stark (1954) appears to be incorrect, at least for the A/J mouse. Their theory assumed that the maxillary and nasal processes are completely separated and that they subsequently fuse, or in the case of a cleft lip, fail to fuse. Stark (1954) believes that the epithelia of the processes fuse first and the cleft lip results from a pulling apart of this epithelium. Scott (1966) and McNall, Coursin, and Sloan (1967) agree with Stark. Stark and Scott also agree that incomplete penetration of the mesoderm into the epithelial nodes will result in a cleft.

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DEVELOPMENT OF THE FACIAL COMPLEX

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The attempt to identify the more important information in the area of facial growth requires considerable selection of data and concepts. Because the ultimate use of such information is applied therapy, I have tried to identify those points which have been important in influencing orthodontic treatment since the turn of the century. The required brevity and simplification do a certain injustice on one hand, but on the other they do highlight differences in concepts.

The turning point in the selection of material has been concerned with the relative influence of nurture and nature in determining the size and shape of the face and dentition. Concepts of biology, whether based on "known" or fictional "facts," extend deeply into spheres of social and economic life. One's concept of the ability of some environmental factor to alter the genetic constitution has bearing on his interpretation of the etiology of a disease, the methods of treatment, definitions of normal and abnormal, as well as what (if any) prophylactic procedures are of benefit.

The reader should also be alerted to another viewpoint (bias?) which has been utilized. As far as possible, I have utilized the null approach to identify reliable and/or relevant information. Unless the results from a given study have been proven to be different from results from a control group (normal growth including variation), it has not been rejected. While such a tactic is useful in sifting the literature to identify information, there is some risk in overlooking concepts which may ultimately prove to be correct.

NORMAL GROWTH

Facial dimensions are relatively well developed, in comparison to most body dimensions, by the time birth occurs. Upper face width is nearly two-thirds of its adult size while face height and mandibular length are one-third of their adult dimensions. Calcification of the deciduous teeth begins halfway through gestation and proceeds slowly till birth, when the total mineral weight is only about 0.5 gm. Calcification of the permanent dentition begins at this time and by two or three years of age, there are 10 deciduous and 14 permanent teeth packed into the maxilla between the orbits and the oral and nasal cavities. There are an equal number of teeth in the mandible—covered by a thin layer

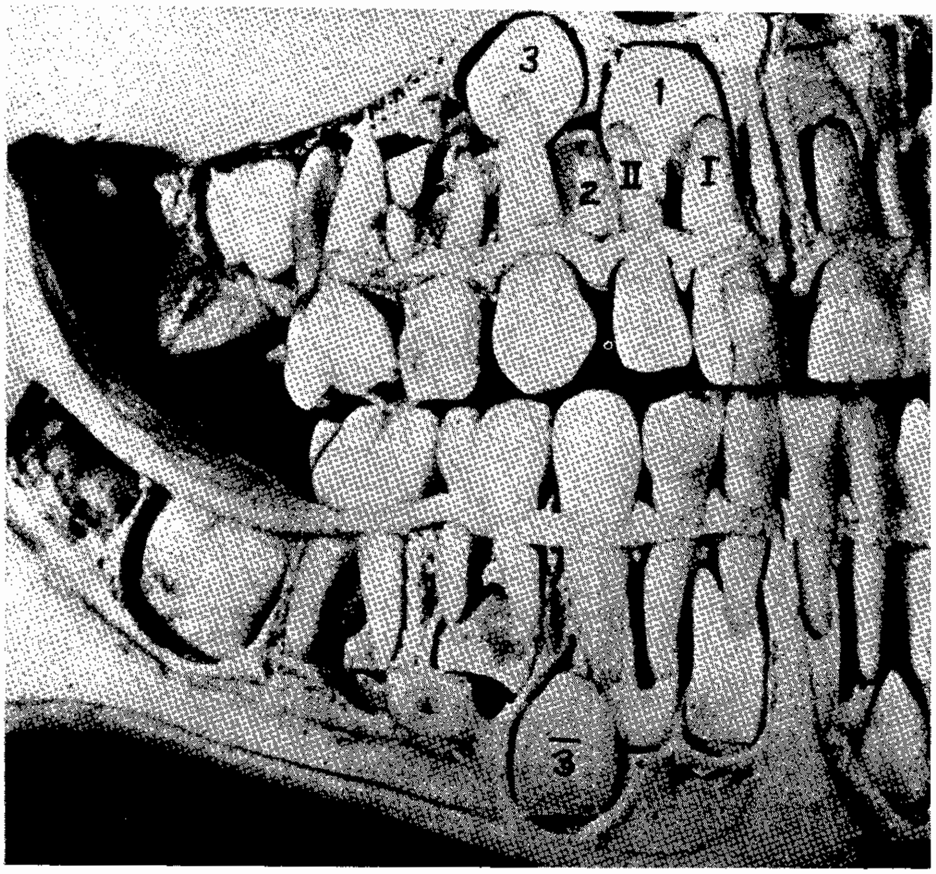

FIGURE 1. The facial skeleton of a child approximately five years of age. Note the thin layer of bone covering the rest of the teeth. Reproduced, by permission, from Diamond (1944).

(2-3 mm) of bone, some muscle, nerves, and skin (Figure 1). At this age the external width dimensions of the face are approximately 85% of their adult size, while the anteroposterior mandibular length is two-thirds of its full dimension (Figure 2).

Mandibular length in absolute dimensions, one of the slower developing dimensions of the face, increases only 37 mm (1¼″) after three years of age. The total increase in width of the mandibular dental arch from the time teeth first erupt until adulthood is only 3 mm (1/10″), and this minute increase is complete by age nine (Figure 2). One is given the illusion that this increase is greater because permanent molars are added to the posterior of a diverging V-shaped arch. In the maxillary arch there is, on the average, a 6-mm increase in width which is more or less continuous from two years of age to 17 or 18 years. In other words, by the time the child is trying to use connected speech, there is little growth left to occur in the face. Within the dental arches, the changes are even smaller and consist almost exclusively of increases in

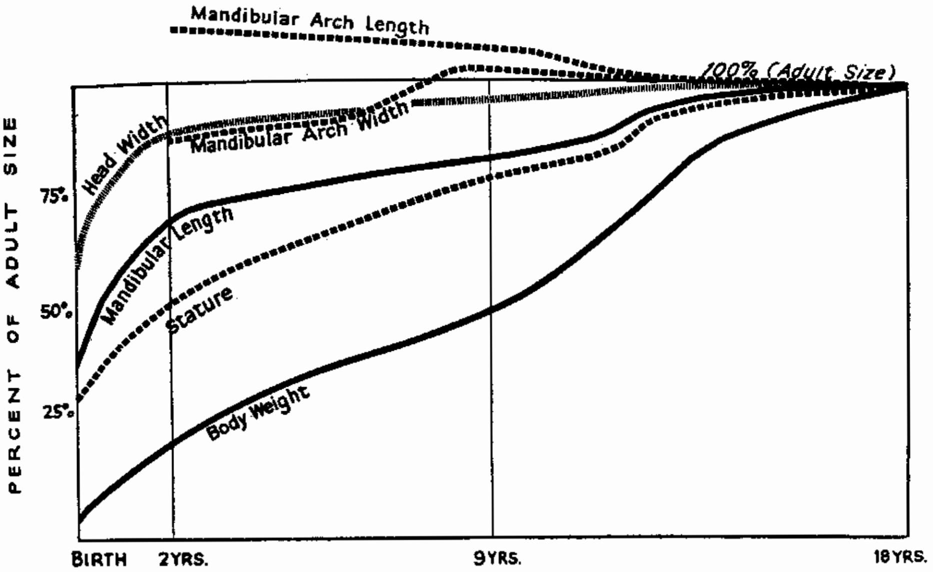

FIGURE 2. Growth of various physical dimensions, graphed as percentage of adult size.

length from the eruption of the permanent molars at 6, 12, and 20 years of age. The reader who is interested in longitudinal dimensional changes of the face and dentition could begin with the writings of Meredith (1966), Moorrees (1959), Sanin (1969), and Savara (1968).

BACKGROUND

Before proceeding, it is important to define as well as possible the limits of influence exerted by nongenetic factors on the growth of the facial skeleton. Explicit in every therapeutic procedure is the principle that an alteration of the environment will produce an alteration (preferably beneficial)in the organism. Implicit is the assumption that the disease or malformation was either produced by an inadequate environment or a genetic deficiency that can be compensated for by use of a supplement, such as with diabetes and insulin.

From today's vantage point, we can describe the dominant orthodontic concept of the early part of this century as far more environmentalistic than that of the last two decades. A reasonably clear statement was provided by E. H. Angle (1907, 1928, 1929), who held that a Class II malocclusion, for example, was attributable to an underdeveloped mandible. This was the result of faulty environment in which the "ideal" alignment and interdigitation of teeth as intended by the "great watchmaker" did not reach "full expression." For those who accepted this permise it was not illogical to direct therapy toward using appliances to establish "normal function" to recover the lost "normal growth" of the mandible.

The current expression of this concept is embodied in the terms *functional orthodontics* and *facial orthopedics* and is more widely held in Europe and

Latin America than in this country. Besides this belief in the ability to influence growth, most environmentalists also adapt a closely related fundamentalist concept of a fallen occlusion, that is, that faulty environment has inhibited full expression of the inherent potential for ideal occlusion. The notion that normal occlusion should be the same for all individuals requires that the genetic determinants of tooth size, size of the mandible and the maxilla, the size of the facial musculature, and so on, are one and the same or else under common control. This is, of course, in conflict with the concepts and evidence pertaining to random assortment of dominant and recessive genetic information as expressed in post-Mendelian and more modern theories of inheritance.

Most so-called malocclusions are biologically normal. What is labeled a malocclusion is merely inherited biologically-normal variation in size of facial and dental structures. The dental profession has transformed this concept into anatomic terms and speaks of "tooth relationships." (Overjet, Class I, Class II, and Class III describe certain anteroposterior incisor or molar relationships; crossbites describe either lateral or anteroposterior relationships; while overbite describes tooth positions in a vertical plane.) A malocclusion is not a pathology; it is a cultural definition of deviation from socially defined esthetic standards. With few exceptions, the label *malocclusion* describes biologically normal variation. The implications of such labeling as it affects who "needs" orthodontic therapy will be discussed later.

To return to examination of the relative importance of environment and heredity, one can begin by noting that bone cells are quite uniform in size. It follows, then, that differences in size of facial skeleton between individuals and differing rates of growth within an individual depend upon differences in numbers of bone cells, that is, the number of mitoses of the mesenchymal derivatives. The cycle in which cell division is controlled by the DNA of the chromosomes has been sufficiently well elucidated during the last two decades that one may state that any environmentalist who wishes to alter the size of a bone would have to postulate some sort of a mechanism by which the pressure on the teeth is translated to the metabolizing cells of the bone and then to their genetic stuff, the DNA, to somehow increase its reproductive capacities. At the present time it is not feasibly to formulate such a hypothesis which is consistent with our biochemical and genetic knowledge.

In comparative studies, there is no scientific evidence that either nutritional deficiencies or infectious diseases cause a diminution of the ultimate facial dimension or increase the incidence of malocclusion (Horowitz and Hixon, 1966). Studies of individuals with long-term respiratory allergies, of mouth breathers or of persons with an open-mouth facial posture show no differences in facial or in dental arch dimensions (Miller, 1949). In fact, Linder-Aronson and Backstrom (1960) noted that "certain skeletal morphology predisposes the individual to mouth breathing." Except for a form of hypothyroidism due to iodine deficiency, the impact of the endocrines on bone size is essentially the function of the gentically controlled secretory level of the cells of the various glands and the central nervous system (Talbot and Sobel, 1947).

While such an interpretation of the impact of nutrition, disease, and endocrines is rather widely accepted in this country today, opinion is divided as to whether or not physical force can influence facial growth. The appliances of both groups are limited to applying pressure to teeth. One group holds they are influencing bone growth, the other that they are moving teeth within bone. In summary, the evidence to be presented does not completely resolve the question of the degree to which nontraumatic environmental factors can provide a long-term influence on facial dimensions, but it does indicate that as of 1970 there is no research which indicates that a physical force has a significant (1 or 2 mm) influence which will persist into adulthood.

Comparisons cannot be made with the changes in cranial shape resulting from head binding. One reason is the passive ability of the intromembranous cranial bones to conform to brain size even in cases of microcephalia or in hydrocephalus. Another difference is that the mandible is suspended by a muscle sling. The muscles of mastication, the suprahyoids, and the facial muscles help position the bony derivative of the first branchial arch, the mandible, somewhat like the bony derivative of the second arch, the hyoid bone. The formation of the location of the temporomandibular joint and the eruption of teeth are secondary in determining mandibular position. Support for this suspensory role of muscles can also be found in patients with bilateral condylectomy. Loss of condyles does not initially impede function except to eliminate protrusive movements, a consequence of those particular muscles being attached to the fractured or excised condyles (Swanson, 1959). The long-term adaptive changes which often result in an open bite suggest a functional role for the condyles.

Ramfjord and Hiniker's (1966a, b) demonstration that either anterior or posterior displacement of the mandible is only temporary, irrespective of changes in occlusion, permits one to reinterpret the earlier study of Breitner (1940), which implied that mandibular growth could be altered. A striking example of the relative long-term immutability of the muscles of mastication in the vertical direction can be found in the study of Logan (1968) dealing with recovery of the dental-facial complex after orthopedic traction for scoliosis. The Milwaukee brace had been used for the treatment of scoliosis, producing a dramatic reduction in face height in some individuals (Figure 3). The rebound again indicates that the impact of physical forces is transistory (Figure 4).

The interpretation described incorporates some of the concepts implied in the functional matrix theory developed by Moss and Rankow (1968) from a single patient and it attributes some of the "mechanism" of facial growth to cartilage (Scott, 1953). The cranial and facial sutures have been cast in a passive role instead of actively contributing to facial growth (Weinmann and Sicher, 1947).

Another expression of the long-term stability (immutability) of the musculature can be found in studies of arch width several years after treatment to widen the arches (Walter, 1953, 1962; Reidel, 1960; Lucchese, 1964). While

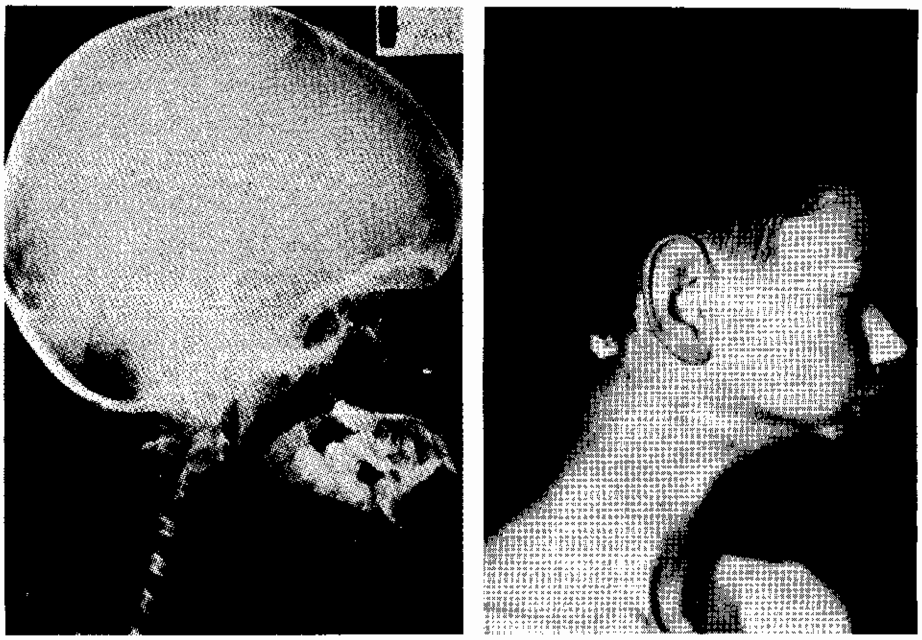

FIGURE 3. Dramatic reduction in face height resulting from use of the Milwaukee brace for correcting scoliosis. Reproduced, by permission, from Logan (1968).

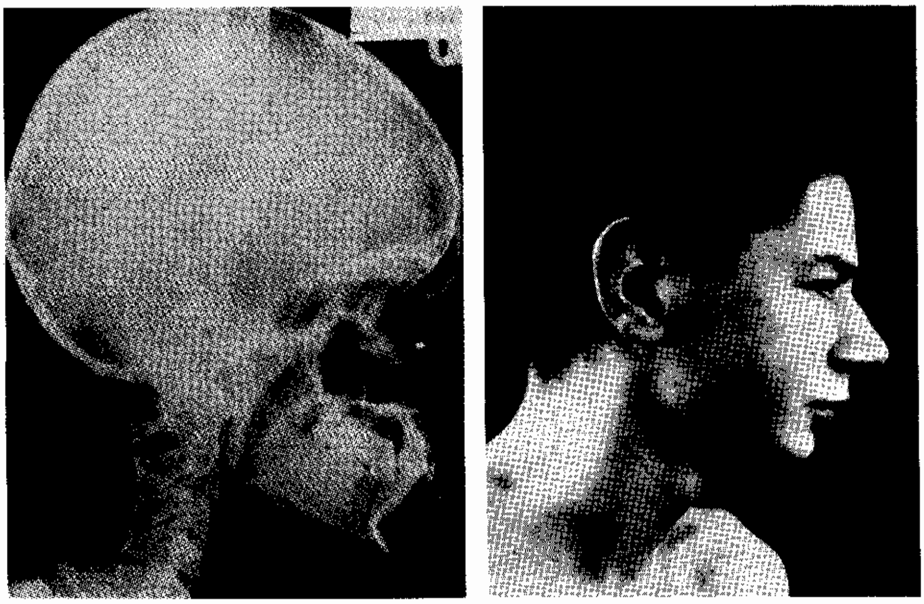

FIGURE 4. Later restoration of normal face height after discontinuing the brace treatment (same patient as in Figure 3). Reproduced, by permission, from Logan (1968).

the mandibular arch width returned to its original dimension on the average, it does appear that the maxillary arch is slightly more mutable. Some of our undocumented evidence indicates that the position of the lower incisor after treatment will tend to return to its original position (± normal variation in growth).

There are two implications which flow from the studies cited. Face height, dental arch width, and, to a lesser extent, lower face length are related to a balance of the musculature. Secondly, the relatively insignificant forces generated by the so-called functional or orthopedic appliances at best produce only transitory alterations in facial dimensions. Thus, on the average, stable treatment for crowding of the dental arches consists of the extraction of teeth (usually bicuspids) and the utilization of this space for alignment without altering mandibular arch dimension. Teeth in the maxillary arch are then adapted as closely as possible to conform to the alignment of the lower dental arch.

The recent studies (Björk, 1953, 1963, 1964; Björk and Kudora, 1968) which have utilized metallic implants in the mandible and in the maxilla to provide fixed landmarks for measuring, as well as the study of Weinstein et al. (1963), have tended to confirm the argument that post-eruptive changes in tooth position result from changes in muscle balance. With a horizontal direction of mandibular growth, the mandible is thrust into the facial musculature and there is a reduction in arch length as the lower incisors are uprighted. Arch width is reduced and the lower anterior crowding increases (Figure 5). Where

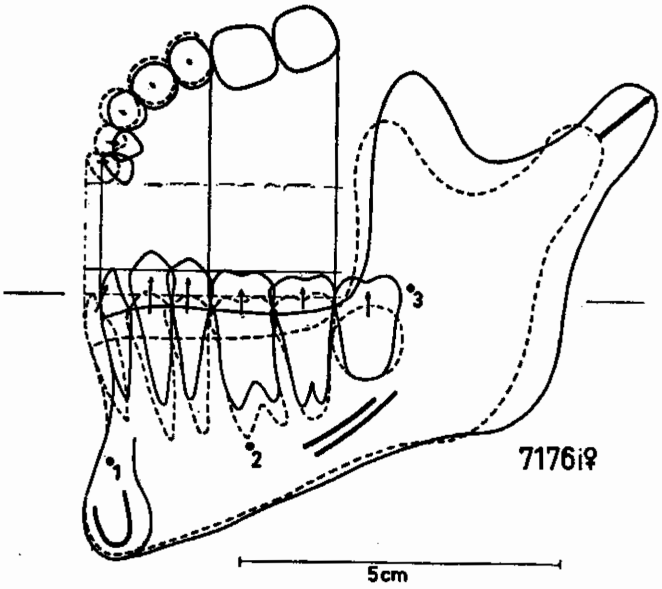

FIGURE 5. Case illustrating extreme direction of sagittal growth at the condyles. Broken line = age 10 years, 6 months; solid line = 15 years, 6 months. Reproduced, by permission, from Björk (1963).

the pattern of mandibular growth is in a more vertical direction there is an increase in arch width and the incisors move forward to reduce dental crowding (Figure 6). It is worth noting that there has been resorption in the inferior part of the mandible in the area of the masseter and the internal pterygoid muscles. Similar variation in pattern has been found in the maxillary complex (Björk, 1964). These observations tend to reinforce an observation that bone form is subject to slow plastic deformation while the musculature is elastic in nature. It is easily stretched, but rebounds. They also serve to illustrate how variations in growth patterns influence the dentition, why some therapeutic successes can be attributed to normal variation in growth, and why it is difficult to separate the impact of therapy from variation in growth. The long-overlooked low relationships ($r = 0.4$ to $r = 0.6$) which exist between occlusal changes (overjet, molar relationship) and facial growth are now understandable (Carlson and Meredith, 1960; Maj and Luzi 1967; Greene, 1968).

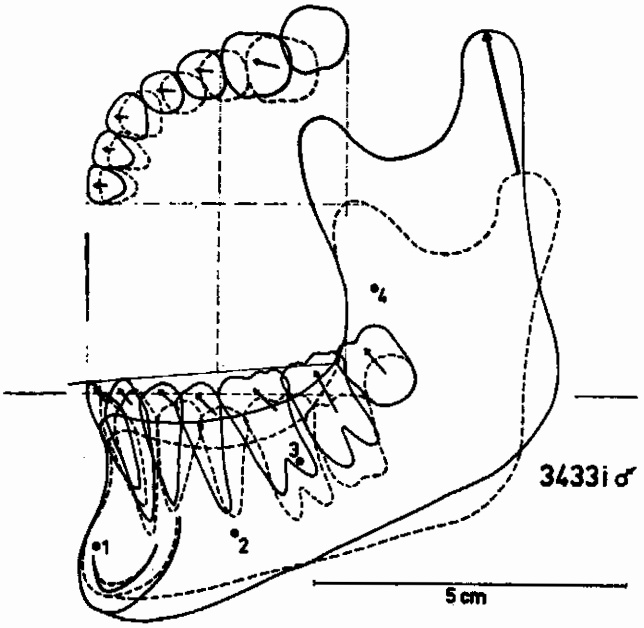

FIGURE 6. A case representing extreme vertical direction of growth at the condyles. Broken line = age 11 years, 7 months; solid line = age 17 years, 7 months. Reproduced, by permission, from Björk (1963).

GROWTH PATTERNS

In the 1930s several longitudinal studies of facial growth were begun. The explicit objectives were to measure growth so as to better understand growth and development. Besides measuring the influence of treatment, there was an implied ability to predict growth. This objective is inconsistent with modern genetic theory because it assumes that individual phenotype (past growth) could foretell unexpressed phenotype (future growth) without knowledge of the individual's genotype.

Nevertheless, it is meaningful to examine the investigations dealing with this segment of research and to examine the two statistical procedures which colored earlier interpretation of the data. One was the use of the average in longitudinal data, with the interpretation that this portrayed normal growth and therefore growth of the individual. This is rather misleading where, as in the face, variations from the average may be as great as or greater than the average change (Meredith, 1960). For example, between 11 and 12 years of age the mean increment for upper face height (nasion-prosthion) is 1.6 mm, with a standard deviation of 1.1 mm. The mean adolescent growth spurt for this dimension during one year is only 2.4 mm, with a standard deviation of 0.8 mm (Savara and Singh, 1968).

Misinterpretations of the correlation coefficient also appear in the facial growth literature. Statistical significance has sometimes been interpreted as implying nonexistent cause-effect relationships. More frequently the part-whole phenomenon has been overlooked as a factor which inflates correlation coefficients. For example, correlations between the size of a body structure at age 12 and at age 20 are high because the dimension at age 20 includes size at age 12 plus growth from 12 to 20 years. If one's objective is to measure growth relationships, he can obtain an estimate by correlating size at 12 with increase (growth) from 12 to 20 and avoid the part-whole artifact (Horowitz and Hixon, 1966).

Table 1 displays selected size/gain relationships from the face and body.

TABLE 1. Selected size/gain relationships from the face and body.

Dimension	*Correlated with* r	*Age Span*
Stature at 6 Yrs.[*]	0.07	6-18 Years
Body Weight at 9 Yrs.[*]	0.21	9-18
Bizygomatic Diam. at 5 Yrs.[*]	0.09	5-11
Nose Depth at 8 Yrs.[†]	0.29	8-14
Upper Lip Protrusion at 8 Yrs.[†]	−0.16	8-14
Upper Face Depth (APOC-ANS) at 5 Yrs.[‡]	0.10	5-15
Mandibular Length (APOC-PO) at 5 Yrs.[‡]	0.15	5-15
Mandibular Length (Co-Po) at 12 Yrs.[§]	−0.09	12-20
Upper Face Height (N-ANS) at 5 Yrs.[‡]	−0.11	5-15
Lower Face Height (ANS-M) at 5 Yrs.[‡]	0.15	5-15
Overbite at 12 Yrs.[§]	−0.31	12-20
Maxillary Arch Width at 9 Yrs.[‖]	−0.15	9-15
Mandibular Arch Width at 9 Yrs.[‖]	−0.41	9-15

[*] Meredith (1965)
[†] DeKock, Knott, and Meredith (1968)
[‡] Carol, Knott, and Meredith (1966)
[§] Björk and Palling (1955)
[‖] Knott (1961)

TABLE 2. Size/gain relationships, including those for predicting mandibular growth.

Selected Angles	*Relationship with* r	*Subsequent Change*
Mand. Plane – F-H at 7 Yrs.*	–0.07	Mand. Growth 7-17 Yrs.
S-N-Po at 7*	0.38	Mand. Growth 7-17
Facial Plane – F-H at 7*	0.22	Mand. Growth 7-17
"Y Axis" – F-H at 7*	–0.08	Mand. Growth 7-17
S-N-A at 12†	0.05	S-N-A Change 12-20
S-N-B at 12†	0.03	S-N-B Change 12-20
Incisor-Mand. at 12†	–0.16	Change 12-20

*Lande (1952)
†Björk and Palling (1955)

Table 2 includes those in current vogue for predicting mandibular growth. In no instance does the correlation exceed $r = 0.4$ where the coefficient of determination (r^2) allows for a 16% reduction of the second variable. The concept that study of a child's past growth is useful in portraying his future growth is often expressed. Yet the results of Table 3 indicate again that phenotype tells nothing of unexpressed growth changes. With regard to predicting facial growth there is some virtue in an approach using increment data as opposed to norms. To be more specific, Table 4 illustrates that the standard deviation of growth changes from ages 12 to 20 is approximately half as great as the standard deviation at age 20. Stated in another form, if one finds virtue in attempting to predict facial growth for an individual, the best available technique is to add the average remaining growth to the dimension presented by the child as he is. The error in prediction will be equal to the *SD* of the growth change.

The orthodontist is interested in alignment and interdigitation of teeth and much of his interest in prediction centers around a stable therapeutic result. Since mandibular arch width shows no change after age nine (on the average), since the lower incisors apparently show little change in relation to the man-

TABLE 3. Gain/gain relationships; i.e., past growth as a predictor of future growth.

Growth Dimension	*Age Span*	*Correlated With* r	*Age Span*
Stature*	1-5 Yrs.	0.11	6-18 Yrs.
Body Weight*	6-9	0.24	9-18
Face Ht. (N-M)†	5-9	0.17	9-15
Upper Face Ht. (N-ANS)†	5-9	–0.04	9-15
Dental Ht. (Pr-Id)†	5-9	–0.18	9-15
Mand. Length (Co-Po)§	6-9	0.11	9-12
Mand. Length (Po-Go)‡	5-8	0.45	8-11
Max. Bimolar Width‖	9-11	0.21	11-14
Mand. Bimolar Width‖	9-11	0.13	11-14

*Meredith (1965)
†Jones and Meredith (1966)
‡Harvold (1963)
§Meredith (1961)
‖Knott (1961)

TABLE 4. Predictability of facial change as a result of measures of average growth and variation. Adapted from Björk and Palling (1955).

	Mean Increase (Age 12-20)	*Standard Deviation of Increase*	*Standard Deviation (Age 20)*	*Ratio SD Increase/ SD Adult Size*
Angle S/N/A	0.8°	1.5°	3.7°	0.43
Angle S/N/B	1.5°	1.6°	3.7°	0.43
Angle A/N/B	–0.7°	1.3°	2.6°	0.50
Incisor-Mandibular Plane Angle	–1.7°	4.6°	7.2°	0.58
Mandibular Length	17.2 mm	3.8 mm	5.9 mm	0.64
Difference in Maxillary and Mandibular Anteroposterior Growth (Ar-A/Ar-B)	4.5	2.0	4.0	0.50

dible (on the average), and since mandibular dental arch expansion relapses (on the average), then the best estimate of long-term stability of treatment rests upon maintaining existing mandibular dimensions and adapting the maxillary teeth to the mandibular arch. It is important to reiterate that the relationship between facial growth and occlusion or changes in occlusion is low. While most therapy and some research is predicated on the assumption that a change in jaw relationship produces a direct change in anteroposterior molar relationship, the actual relationship is positive, but with an *r* of only 0.4 to 0.6, for molar relationships and for incisor overjet (Carlson and Meredith, 1960; Greene, 1968; Maj and Luzi, 1967). Against this background, one may consider the relative value of the orthodontist's concern with prediction of facial growth as opposed to concern with dental arch changes.

THE IMPORTANCE OF OCCLUSION

With regard to the biologic necessity of teeth it is obvious that one can survive in this culture without teeth and meet adequate nutritional requirements. Many edentulous individuals attest to this. Studies on digestion have indicated that mastication is of some importance for eating fried foods and green peas and of no consequence for eating potatoes, fish, and bread. From the standpoint of digestion, teeth are a convenience but not a necessity (Farrell, 1956). Further, most malocclusions do not seriously affect masticatory performance aside from "open bites" or nonocclusion (Hixon, Maschka, and Fleming, 1962).

Teeth facilitate, but are not essential in, the articulation of a few labiodental and linguodental phones. As with masticatory efficiency, the open bite or nonocclusion is most telling in the production of the sibilants /s/, /z/, /ʃ/ (Spriestersbach, 1966). With regard to longevity of the dentition, crowding causes some increase in dental caries of the lower anteriors (five surfaces on the average in a young adult) and an increase in gingivitis (Hixon, Maschka, and Fleming, 1962). What relationships exist between gingivitis and periodontal pathology (pyorrhea) is undocumented despite a popular belief that a high correlation exists.

It is worthwhile noting that some distinctly differing definitions of malocclusion are in common usage. This implies different standards in determining who "needs" treatment. Obviously a malocclusion is an occlusion that is not "normal," but one can identify two distinct definitions of occlusion and at least three different concepts of normal. The differing concepts of occlusion are these:

1. Irregularities of alignment and interdigitation, i.e., "crooked" teeth, involving tooth size, dental arch size, size of mandible, muscle sizes, size of maxilla, and their relationships to one another—an anatomical definition.
2. The dynamic intercusping associated with chewing, where malocclusion refers to occlusal trauma or the so-called "T.M.J. syndrome" (of which perhaps 90% are iatrogenic)—a "gnathological" definition.

If we identify our interests with crooked tooth straightening, it is sufficient to mention that static malocclusions (irregularities of the teeth) seldom produce muscle spasm (functional malocclusions).

The problem of defining "normal" is expressed in the following possibilities:

1. Statistical or average:
   a. Most frequent, usual, popular, the mode.
   b. Typical—a statistical approximation is sometimes considered to be the mean with "normal" variation defined by ±2 *SD*.
2. Functional—does it work:
   a. Health, i.e., it "does its thing" normally. Please note that *function* has a slightly different meaning than that implied in the previous paragraph.
   b. Not harmful, not painful, and nonpathologic.
3. Idealistic—the way it "ought" to be:
   a. Orthodontic (Angle's Old Glory).
   b. Gnathologic.
      (1) cuspid protection is normal.
      (2) group functon is normal.
   c. Anthropologic—abrasion is normal.

Most gnathologic definitions include unabraded three-point tooth contact. Many also include retruded mandibular position in contrast to a position dominated by the suspensory muscles of the mandible.

ABNORMAL GROWTH

In the perspective outlined in this paper, abnormal facial growth would include cleft palate and cleft lip, Treacher-Collins syndrome, orofacial dysostosis, cleido-cranial dysostosis, idiopathic hypercalcemia (elfin face), Down's syndrome, cranial and/or facial stenosis, dwarfism, gigantism, and acromegalia.

In all, genetic transmission is important. Since the incidence of all except cleft palate is low, and research and therapy concepts related to abnormal growth do not form a cohesive interpretation, this section is limited to a few generalizations regarding cleft lip and palate. The patient with an isolated cleft lip (without palatal involvement) has a cosmetic problem to be handled by the plastic surgeon, while the individual with an isolated cleft palate is concerned with problems of speech. Neither demonstrates any unusual patterns of growth. Even with cases of combined cleft lip and palate, the problems of abnormal facial development have decreased considerably in the last two decades with the decrease of the collapsing or crushing surgery of the early 1900s. The more recent and conservative plastic procedures (those which produce little scar tissue) have a minimal influence in altering the growth of the maxilla. In these cases, the deformity is relatively minor and can be corrected in a few weeks with expansion of the maxilla before preparing the patient for more extensive routine orthodontic procedures or for a bone graft.

For the unilateral cleft lip and palate, this means that early orthodontic intervention is usually not indicated. Expansion of a maxillary dental arch at the age of 12 is sufficient and precludes some 10 years of essentially useless therapy. The claims that palatal-shelf development can be stimulated are not consistent with our other biologic information. The null hypothesis would require demonstration of results that exceed the normal variation in growth of untreated cases such as presented by Pruzansky (1964).

Orthodontic treatment of bilateral cleft lip and palate is more complicated than that for unilateral cleft, since growth of the nasal septum may produce an initially undesirable cosmetic impact—the "wolf snout." Whether this abnormality of facial growth is best handled by orthodontic restraint or surgical intervention depends upon the size of the premaxillary segment, the long-range plans for the patient, and the respective skills of the orthodontist and the surgeon. I find difficulty in generalizing about growth and the therapeutic implications except to note that the "wolf snout" is reduced with age.

Again, when discussing abnormal facial growth, the diagnosis of abnormality is to a large extent a cosmetic interpretation; that is, plastic surgery is indicated when a person's appearance deviates from esthetically acceptable standards of the beholder. If the deviation involves teeth instead of the face, orthodontic services may be requested. The esthetic values employed to determine an abnormality are implicit in the World Health Organization statement: "An anomaly should be regarded as requiring treatment if the disfigurement or functional defect is or is likely to be an obstacle to the patient's physical and emotional well-being" (Grainger, 1967).

Since irregular teeth rarely interfere with mastication and speech, the definition of malocclusion then becomes essentially an esthetic definition of or deviation from a culturally determined norm. These deviations are usually described in anatomic terms and cloaked with biologic implications. Decisions regarding who "needs" treatment (and attempts to develop indices of malocclusion) for public and private insurance programs usually avoid the primary motivation for treatment: the patient's (parent's) subjective evaluation of his appearance in relation to his concept of a culturally acceptable standard.

There is little doubt that, in general, the social and psychological values regarding the physical appearance of the face and dentition are more important in this culture than are the biological necessities of good occlusion. An index of the value system is provided by national expenditure of money. The amount spent for all health care is about equal to that spent for automobiles. The expenditures for dentistry (10% of the health bill) are one-fifth of that expended for alcohol and about equal to that expended for jewelry or for beauty parlors and barber shops. It is about twice that expended for funerals and burial expenses ("Expenditures and Prices," American Dental Association, 1969).

CONCLUSION

If one strips away conventional justifications for a clinician's (orthodontic, speech, surgical) interest in facial growth and maturation, considerations regarding various esthetic criteria become paramount, even to the extent that they essentially describe the limits of normalcy. In the case of orthodontics, "non-normal" (even a handicapping malocclusion) usually describes social reactions to esthetic values rather than biologic handicaps. This state of affairs is rather fortunate for the orthodontist who employs mechanical devices which can influence tooth position but do not have a measurable influence on the muscular and bony tissue which are encompassed within the various facial dimensions. Elective alteration of facial dimensions is limited to surgical procedures.

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DEVELOPMENT OF NEUROMUSCULAR SYSTEMS UNDERLYING SPEECH PRODUCTION

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It is necessary, initially, to define the term *speech* as it will be used in this paper. It will refer strictly to the acoustic signal of oral communication. That is, consideration will be restricted to the neural processes involved in the generation of muscular activity associated with production of that signal. There is no intended reference to neural processes involved with reception, integration, and utilization of symbols in the communication process, or what might be referred to as neural mechanisms of language. Granted, this rather dichotomous definition of neurological speech and language processes is greatly oversimplified, but because of space limitations, it will have to suffice.

This presentation, then, will cover a relatively restricted aspect of the neurological processes involved in oral communication. The neuromuscular processes of speech generation were chosen because the prime focus of this workshop is upon the oral-facial complex and its function. Therefore, consideration of the neural mechanisms underlying language is probably of less interest than those underlying muscular activity associated with speech production.

In order to bring into perspective the many needs for further research on how the human organism develops the intricate and precisely coordinated muscular patterns associated with speech production, it appears necessary to review information from a wide variety of areas of knowledge. It is impossible to deal with most of the material in any critical depth at all. That is, it would be impractical to point to numerous specific research studies, their limitations of technique, and whether or not the conclusions of the investigators seem appropriate or inappropriate. Rather, a major portion of the reference material will be from relatively current comprehensive reviews of research information or examples of research in specific areas.[1] As a consequence, many of the statements made here regarding what is "known" about certain aspects of this topic need far more critical and extensive qualification than is practical or, perhaps, necessary to highlight needs for further research.

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[1] There are many instances here where only one or two references are given as examples of pertinent research although numerous studies could be recognized; omissions do not imply an evaluation of the research as unworthy of mention.

AFFERENT SYSTEMS IN SPEECH PRODUCTION

It is well documented that efferent neural systems are dependent upon afferent systems for appropriate function. For example, Houk and Henneman (1968, p. 1695) state, "Complex movements require the participation of many types of feedback. . . ." They point out that sensory receptors in the skin of moving body members seem to be required for exploratory behavior and grasping, that posture and balance require feedback from the vestibular system, and that a large part of muscular activity, in general, seems dependent upon visual information. Even though specific examples of prime afferent feedback systems may be given for some types of activities, the integration of all afferent information that influences any act is exceedingly complex.

Nevertheless, the positive research findings that show the integration of afferent information to be requisite for efferent patterning are so numerous that a physiological separation of efferent and afferent mechanisms in the normally functioning human seems untenable. Rather, while sensory and motor systems may be identified anatomically, their interaction is so necessary for appropriate muscular patterning that physiologically they must be considered in terms of the "sensorimotor systems." However, the major portion of research dealing with those systems has been concerned with bodily posture and limb movements, and there is much less definitive information about how those systems operate in acts such as generation of the speech signal.

Of those afferent systems that may be involved in muscular patterning for speech production, the process of audition and the tactile-proprioceptive afferent systems would seem to be those primarily involved. An early model of speech production by Fairbanks (1954) suggested that the speech signal, via the auditory process, is fed to what he called the "controller unit" of the speech musculature system. His model assumed that the speech musculature operates in conjunction with the auditory system as a closed servomechanism, and he relegated what he called the "somesthetic" afferent systems to a secondary role by indicating that although they may supply information about the "mechanical operation" of the speech mechanism, they may give little direct information about its output. However, as indicated by the review provided elsewhere in this *Report* by Ringel, there is a growing belief that what Fairbanks referred to as somesthetic systems play a potentially stronger role in speech musculature patterning than he suggested.

Audition

The importance of auditory monitoring to the development of and maintenance of speech production cannot be denied. Deaf children routinely do not develop speech production capability. Some can develop intelligible speech with assistance, but they seldom develop speech that is perceived as normal. A person who becomes deafened after having learned to produce speech manifests a slow deterioration of the speech process (Sataloff, 1966). Typically, this deterioration is observed first for consonants and subsequently for vowels (Carhart, 1960).

These observations seem to support the contention of many (for example, Chase, 1968) that the auditory signal is that component of the total sensory experience associated with speech generation containing all of the information in the "target," or end product, of speech musculature patterning. Hence, the deaf child has considerable difficulty in learning to produce acceptably many components of the speech signal. Moreover, while the adventitiously deaf person's speech musculature can operate with reasonable precision for some period of time, through loss of the auditory "target" (with all of its complexity) the system gradually loses function. Those speech elements requiring the most precise muscular patterning are affected first.[2]

The effects of blocking the auditory feedback process by masking the subjects' speech via high-level noise have been well known since 1911 (Lombard). Other than raising the intensity level of the voice, speakers routinely show little disruption of articulatory capability. This lack of seriously detrimental effects upon production of intelligible speech by such masking, as well as the lack of immediate deterioration of speech of the adventitiously deaf, seems to contradict Fairbanks' concept (1954) of a closed loop feedback system for speech generation. That is, if such a concept implies that the system's operation is dependent upon its feedback portion, severely deleterious effects on speech generation would be expected when a person either becomes deaf or has his own speech signal masked. Therefore, it must be concluded that intraoral sensations can provide cues for positioning of the speech musculature once the appropriate patterning has been learned, and they can continue to do so in the absence of auditory feedback.

Delayed auditory feedback, however, does have a significant effect upon speech production capabilities, and that phenomenon has been used by some to support the suggestion that speech production is dependent upon auditory monitoring. Chase (1968) provides an excellent review of research with delayed auditory feedback, and later discussion in this paper will suggest why its effects upon speech need not be interpreted as meaning that operation of the speech musculature is dependent upon audition.

Somatic and Visceral Afferent Systems

In contrast to the relatively minimal immediate effects loss of auditory feedback has upon speech, the serious detrimental effects on muscular function produced by deafferentation have been observed since the last century (Mott and Sherrington, 1895). Continued observation of deafferentation, via techniques such as dorsal root sectioning, has led some authors (e.g., Henneman, 1968b) to conclude that movement is essentially abolished upon loss of bodily

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[2] In this *Report,* Ringel provides a very concise discussion of evidence suggesting that acoustically acceptable speech may tolerate much greater variability in muscular patterning for vowels than consonants.

afferent information in the central nervous system. This comparison between the effect loss of auditory feedback has upon speech production and the effect deafferentation has upon general muscular activity suggests that if there is a closed servomechanism involved in the sensorimotor operations underlying speech production, such a role is played by afferent systems other than audition.

Reflex, Tactile-Proprioceptive, and Somesthetic Systems

Before discussing the available information about other afferent systems that may be involved in monitoring speech musculature function, it is imperative to clarify certain distinctions between those systems. It has been well established that a variety of afferent impulses may be brought to bear upon cell bodies of motoneurons of peripheral efferent systems at the segmental or bulbar levels. That is, a variety of afferent influences may be transmitted within lower levels of the central nervous system that assist in bringing about accurate movements and, in some cases, such transmission may result in organized movements.

An example of the latter type of activity is the gag reflex for which stimulation of the visceral afferents in the oral-pharyngeal area may result in an organized muscular event through relatively direct connections with peripheral efferent neurons. Such "reflex" activity is relatively well understood. In addition, however, afferent information from skin and mucosa, muscle tissue, tendons, etc., may also assist in bringing about movement through similar, relatively direct connections. For example, Houk and Henneman (1968) discuss the relative roles of muscle spindles and tendon organs which interact to bring about muscle action that facilitates appropriately timed contractions of muscles acting upon joints. The afferent receptors that may contribute to such function are varied, and their relative contribution is complex and probably not completely understood. It would seem most likely, however, that similar systems must be intimately involved in speech musculature function.

Another afferent system sends information via spinal-cerebellar and, for speech musculature function, bulbar-cerebellar connections to the cerebellum, which, in turn, discharges impulses into efferent muscular systems. It is important to recognize that this type of afferent information, while directly involved with coordination of muscle activity, does not necessarily arise in conscious sensation. For example, Henneman (1968a, p. 1771) states that the cerebellum

> receives a continuous stream of impulses from receptors in muscles, joints, tendons, and skin and from visual, auditory and vesibular end organs. These impulses do not mediate conscious sensations, but they supply the sensory cues essential to control of movement.

Of the many sources of afferent impulses to the cerebellum, those that have been mentioned most frequently as being involved with speech production are tactile and proprioceptive information.

A third type of afferent system is the one which arises in conscious sensation of (1) stimuli applied to the surface of the body or gustatory tract (somatic or visceral touch-pressure systems) and (2) relative positions of structures of the body and rates of changes in those positions (kinesthesia). These somesthetic sensations are transmitted via the lemniscal system to the postcentral gyrus area of the cortex. The somesthetic sensations most frequently mentioned in speech literature as being involved with speech processes are those just mentioned, touch-pressure and kinesthesia.

It is important to note that the peripheral receptors contributing to these three types of afferent systems (that have been grossly described in an oversimplified manner) may be one and the same. For example, muscle spindles, without doubt, contribute to the gamma-alpha loop involved in reflex activity and low-level integration of muscle function; those spindles also contribute to proprioceptive impulses to the cerebellum. It may be that muscle spindles also contribute to the sensations of kinesthesia. Hence, the implications of any study that involves blocking or diminishing of afferent systems potentially involved with speech production must be based upon an analysis of what systems may be involved and where the blocking is introduced. It should be obvious, then, that the complexity of anatomical and physiological relationships of these afferent systems present extreme obstacles to a precise analysis of that type.

For the purposes of this paper, tactile and proprioceptive impulses will refer to the neural information transmitted to the cerebellum for coordination of muscle activity (for example, Henneman, 1968a). These impulses are to be differentiated from somesthetic sensations such as touch-pressure and kinesthesia. Touch-pressure and kinesthesia will refer to conscious sensations arising from afferent impulses that lead to somesthetic sensations that are perceived and have discriminative dimensions (Mountcastle and Darian-Smith, 1968). While such a distinction seems to be assumed by some, the terms *tactile* and *pressure,* as well as *proprioception* and *kinesthesia,* are used interchangeably by many authors, sometimes without definition.

TARGET AND COORDINATION SYSTEMS FOR SPEECH PRODUCTION

As indicated previously, observations such as the lack of immediate deterioration of the speech of a person who becomes deaf indicates that once speech has been learned, the function of the speech musculature is not totally dependent upon the auditory process. Why, then, the deleterious effect of delayed auditory feedback upon the speech process? In some of the more comprehensive reviews of the effects of delay of sensory experience upon muscular behavior (for example, Smith, 1962), there appears to be evidence that those sensory systems which relay target information to the musculature systems perform their function as after-the-fact, error-detecting systems. There is also the suggestion that when two or more such sensory systems are involved, which seems to be the case in most movements, temporal delay of one disrupts muscular patterning. That is, the efferent mechanisms are presented with two different temporal targets. In the presence of the temporal lag between the targets, muscular activity deteriorates since the efferent systems cannot adjust to the inherent gross errors that occur through the inability to approximate both targets.

For speech production, the "other" target, or targets, that seem to be involved in a comparison to the auditory signal probably are comprised of a complex array of afferent information that defies separation. For example, Houk and Henneman (1968, p. 1695) state:

> The manner in which all of the various kinds of control mechanisms are coordinated with proper regard for their priority in different situations and for the sequence and timing of movements is not fully understood.

As already mentioned, the cerebellum can be called the structure of the nervous system primarily responsible for coordination of muscular activity with afferent information from a great variety of receptor mechanisms. In addition to receptors from the auditory system, those from skin, mucosa, muscles, and joints seem to be the most likely mediators of afferent information that is utilized for speech production, that is, primarily exteroceptive, tactile, and proprioceptive impulses.

In this *Report*, Ringel comprehensively reviews current knowledge of oral sensation and perception, the somesthetic capabilities of the oral cavity, and research on the effects of oral afferent deprivation upon speech. A considerable part of that research has been devoted to mapping the two-point discrimination thesholds of the oral cavity and determining intraoral stereognostic capability. There seems to be an underlying assumption that deficits in those two realms of sensory experience may be related to speech production problems.

That damage to the lemniscal system will result in muscular dysfunction seems uncertain. For example, in reviewing the effects of lesions of that system, Mountcastle and Darian-Smith (1968) do not indicate the presence of associated muscular disturbances. For another example, Semmes (1967) reports deficits of stereognosis in the hands of brain-injured adults who demonstrate no muscular problems. In general, it is believed that stereognosis, or three-dimensional shape identification in the absence of visual information, is dependent upon integration of the sensations of touch-pressure and kinesthesis (for example, Mountcastle and Darian-Smith, 1968; Grossman, 1967). If this is so, work such as that of Semmes also demonstrates the lack of a direct relationship between deficient somesthetic sensations and muscular dysfunction. If such a relationship does not exist, the deleterious effect of deafferentation upon muscle function probably should be ascribed to the blocking of (1) the lower-level, more direct afferent-efferent loops or (2) impulses to cerebellar mechanisms.

The studies of oral afferent deprivation, such as those that have utilized surface anesthesia and afferent nerve blocks, probably disrupted different aspects of the oral sensory systems. With respect to the latter type of investigation, there is also some question whether nerve blocks can be introduced that will anesthetize the oral cavity and completely spare efferent neurons (for example, Locke, 1968). Even so, pooling the results of all such studies (again, Ringel, this *Report*) indicates that such desensitization of the oral cavity does not dramatically affect speech musculature function. At least, the speech of subjects in such studies remains intelligible. Therefore, it would appear that even in the presence of anesthetization of oral afferent mechanisms, the auditory process can continue to serve as a target for the speech musculatures to a degree that is sufficient for the production of intelligible speech.

From the discussion up to this juncture, it seems improbable that a deficit of oral somesthesia should be the basis of a speech-learning problem. The work in mapping the two-point discrimination and stereognostic capabilities of the oral cavity (for example, Ringel and Ewanowski, 1965, and Shelton, Arndt, and Hetherington, 1967, respectively) may seem not to have much implication for detecting and understanding deficits of afferent systems that are directly related to sensorimotor function for speech production. However, such an assumption should not be made at this time. There are too many gaps in our current information and too many unresolved controversies regarding the role of tactile-proprioceptive systems and somesthesia in speech production.

For example, much more information is needed regarding the underlying neuroanatomical and neurophysiological mechanisms that transduce and transmit oral afferent information. There is disagreement about the existence of intrafusal fibers (or muscle spindles) in tongue muscles. Storey (1967) briefly refers to the fact that a number of studies do not confirm the presence of muscle spindles in tongue muscles. However, he also cites the work of Cooper (1953) that demonstrates their existence. In addition to Storey's mention of Cooper's work, Crosby, Humphrey, and Lauer (1962) discuss work by Langworthy done as early as 1924, showing positive evidence of proprioceptive sensors in the tongue. At this time, however, it is not known specifically how spindle afferents enter into the cranial nerve system to distribute stretch information to bulbar nuclei or how they might contribute to a gamma-alpha loop via interneurons within the brain stem (Konigsmark, this *Report*).

It has been fairly well established that muscle spindles, along with their afferent neurons, are prime contributors to proprioception (see a number of contributors in Granit, 1966; Houk and Henneman, 1968; and Henneman, 1968c). Not only do they provide proprioceptive information to the cerebellum but they also help regulate muscular activity through the spindle afferent-alpha loop (again, Houk and Henneman, 1968). We also need more knowledge about how afferent information influences speech musculature patterning—not only how proprioceptive information from the tongue is fed into the central nervous system, but whether there exists such a gamma-alpha loop within the brain stem to regulate the numerous muscle groups involved with speech articulation.

And, for a third example, information is needed concerning those receptor mechanisms that contribute to the sensation of kinesthesis. Kinesthesis is mentioned frequently in the literature of speech pathology as playing a prime role in the function of the speech musculature, and it has been assumed by some that the muscle spindles contribute to that sensation. Despite the suggestions in the foregoing discussion that there may be little or no relationship between such a somesthetic sensation as kinesthesis and muscle function, there is disagreement on whether or not muscle spindles do contribute to that sensation.

Mountcastle and Darian-Smith (1968) and Henneman (1968c) conclude that Golgi tendon receptors provide the information requisite for what they term *position sense*, and Henneman concludes that the two types of muscle spindles with their afferent projections contribute little or nothing to kinesthesis. Very briefly, there are two bases for this conclusion. (1) The Golgi tendon organs detect muscle tension and, hence, with the information they send to the central nervous system regarding relative tension loads in opposing muscle groups, they give information about the angle of joints and, hence, position sense or kinesthesia. On the other hand, muscle spindles, or stretch receptors, provide information only about length of muscle, and as a result little or no information about the spatial position of the muscles in which they are contained. (2) There is little evidence that there are direct neural anatomical connections from the intrafusal muscle systems via their spindle afferent axons to receptive areas of the cortex, where it is allegedly necessary for a sensation such as kinesthesia to be distributed.

However, while Mountcastle and Darian-Smith take the same position, they insert (p. 1408) a brief discussion of research by Oscarsson and Rosen (1966), and Oscarsson, Rosen, and Sulg (1966) that demonstrates a relatively direct connection from these muscle stretch receptors in the forelimb of the cat to the somesthetic reception area of the cortex. They also imply that if such a projection system is found for other muscles in other species, the view that stretch receptors do not contribute to kinesthesis may need revision.

On the other hand, Paillard and Brouchon (1968) suggest that among a variety of sensory receptors that potentially contribute to kinesthesis, the muscle spindles may, during active movement, provide kinesthetic information due to their ability to detect the rate of change of muscle length. To support their suggestion, they cite not only the work of Oscarsson and Rosen (1966), but they also refer to research (Albe-Fessard and Liebeskind, 1966) reporting that such neural projections could transmit spindle stretch information to the postcentral cortex gyrus from all four limbs of monkeys. Moreover, Paillard and Brouchon suggest at least four other sources of neural information that may contribute to kinesthesis: joint receptors, cutaneous receptors, tendon receptors (Golgi organs), and "the pattern of motor innervation." The latter potential source of kinesthesis refers to the concept of "motor outflow," and Paillard and Brouchon (pp. 50-51) provide basic references to this concept.

As a final example of much-needed information, firm evidence of the degree to which kinesthesis of some oral structures exists is lacking. While Ringel, Saxman, and Brooks (1967) have demonstrated kinesthesis of mandibular position, comparable direct evidence about the tongue is lacking. The best evidence that kinesthesis of the tongue does exist as a sensory phenomenon is the demonstration of oral stereognosis (for example, Shelton et al., 1967). Even this is indirect evidence since it is based on the assumption that, as mentioned earlier, stereognosis results from integrating sensations of touch-pressure and kinesthesia.

In summary, the effects of adventitious deafness and anesthetization of the oral cavity seem somewhat analagous. That is, in both cases, the precision of consonant productions is most dramatically affected, and the integrity of vowel productions seems most resistant to deterioration. To the extent that the anesthetization studies do, in fact, reflect diminution of afferent innervation without interference of efferent system function, it appears that once the speech production process is learned, obliteration of either the auditory or the tactile feedback affects primarily the more precise and complex movements associated with accurate speech articulation. The immediate effect of anesthetization may be due to the dependence of the efferent systems upon the tactile-proprioceptive information for precise coordination, while the gradual deterioration after onset of deafness suggests that the auditory process may function more as an error-detection system needed to maintain the system's function after the speech production process has been learned. Despite numerous assumptions about the role of somesthesia in speech production, there has been no report of a speech deficit associated with damage to only the somesthetic systems (e.g., touch-pressure and kinesthesia) in persons who sustain damage to the lemniscal system after speech has been learned. Moreover, there is considerable controversy over specific aspects of the neuroanatomical and physiological processes of somesthesia. At present the state of our knowledge of those systems makes it difficult to construct a theoretical framework which suggests that somesthetic deficits and speech problems are directly related.

POSSIBLE DIFFERENCES BETWEEN MATURE AND IMMATURE SYSTEMS

There is some evidence that neurological problems resulting from maldevelopment or lesions occurring before, at, or shortly after birth, and manifested primarily by somesthetic deficits, do present problems of speech-learning. The case studies by Chase (1967), Bosma, Grossman, and Kavanagh (1967), and Rootes and MacNeilage (1967) demonstrate what appear to be congenital deficits of oral somesthetic sensation. Those reports present two children who manifested poor function of oral structures and poor speech in the absence of demonstrable signs of generalized neuromuscular problems. Also, Schliesser (1965) found a relationship between two-point discrimination deficits of the upper lip and the severity of speech defectiveness in a group of congenitally spastic hemiplegic children. These results are rather meager, but they do suggest, at least, that maldevelopment of speech musculature patterning may be, in some way, related to congenital somesthetic sensation and discrimination problems.

It is suggested, therefore, that the muscular activity associated with speech utilizes at least two error-detecting systems in the adult, the tactile-proprioceptive system and the auditory system. Moreover, it seems likely that more direct afferent-efferent connections within the brain stem enter into execution of speech articulatory patterning. For the immature nervous system, however, damage that results in deficits of somesthesia may cause speech-learning problems for a child. Specification of the location at which a central lesion in the young nervous system would result in such a hindrance seems impossible at this time, but the results of Schliesser's study, where subjects undoubtedly had an abnormality in the suprabulbar systems, suggest the need to determine the location of such lesions and the systems that are disrupted. In addition, in describing one of the cases of congenital somesthetic deficits, Chase (1967) states that his findings indicate a central lesion but he was unable to specify its location.

MOTOR COMMAND SYSTEM

In his discussion of one of the cases who manifested congenital somesthetic deficits, Chase (1967) suggests a model of sensorimotor function for speech production that incorporates sensory modalities other than audition in feedback loops to what he calls the sensorimotor programming system. In addition, matching of error-detecting systems is incorporated. However, as in the case of the model by Fairbanks (1954), this model also incorporates the concept of a closed servomechanism.

Again, such a closed servomechanism between the command system for the output of the speech mechanism seems untenable. In addition to the fact that the speech production system continues to operate after a normal speaker becomes deafened, it is apparent that many physiological events take place well in advance of the generation of an acoustic signal (for example, Lenneberg, 1967). Therefore, some type of command system may well drive the speech-producing musculature that is independent of afferent monitoring, or error-detecting, systems.

There is even more persuasive evidence that a command system for speech generation exists having characteristics contradicting such a closed feedback system. The evidence results from the studies of what Daniloff and Moll (1968) refer to as "forward coarticulation." This term denotes the numerous observations (for example, Öhman, 1966; Kozhevnikov and Chistovich, 1965) that the speech articulators may move toward the target position for a given phone well in advance of production of that phone during an utterance, provided that an intervening articulatory target position does not interfere. For example, Daniloff and Moll found that lip protrusion associated with the vowel /u/ may begin as many as four consonants prior to that vowel's production, that is, the

/u/ in "construe." Such data suggest strongly that there exists a "motor command" system for speech production with the capability of determining a target position well in advance, and, moreover, its operation results in movements toward that target position as soon as possible during an utterance.

It is tempting to suggest that the motor command system for speech generation selects its program from a system which has stored words or phrases. That is, it might be that as the central nervous system learns and stores words, phrases, and even utterances of considerable length, the motor command system can select from that storage bank and transmit those utterances into the complex coordinated patterns of movements over their entire duration. The available data do not seem to support such a suggestion. Lindblom's (1963) subjects produced nonsense syllables, and the subjects of Daniloff's and Moll's research showed forward coarticulation across word boundaries of infrequently used word combinations, for example, "since true." It is difficult to contend, then, that storage of learned words or phrases is responsible for forward coarticulation.

Among a number of models of speech production processes, those of Cooper (1966) and Henke (1966) involve motor command systems operating from stored phonological units, or stored characteristics of those units. Moreover, those models, as well as the data referred to, suggest that the command system, operating from a set of stored phonological characteristics, has learned and follows the phonological rules of the speaker's language. Such a system could theoretically discharge into the muscular systems the complex movements for speech generation in advance of their production, and the monitoring systems could thereafter monitor their execution.

THE TOTAL NEUROMUSCULAR SYSTEM ASSOCIATED WITH SPEECH GENERATION

Thus far, the discussion has centered primarily upon the activity of the speech articulators. The complete efferent neural net that generates the speech signal must be viewed as much more complex than the discussion would imply. Concomitantly with movement of the tongue, lips, jaw, and palate, many other muscle groups are active in a complex, highly coordinated fashion.

While it has been assumed for some time that dimensions of the oral pharyngeal cavity vary to assist in the formation of resonance chambers during speech, it has been believed that such changes were the result of movement of the tongue. There is now evidence that even pharyngeal wall muscles should be considered as part of an active articulator in that they apparently contract systematically during speech production (Kelsey, Woodhouse, and Minifie, 1969). Electromyography has shown muscular innervation of intrinsic muscles of the larynx to vary as a function of changes in pitch (Faaborg-Andersen, 1957), and some extrinsic laryngeal muscles appear to contract differentially as a function of vowels (Faaborg-Andersen and Vennard, 1964).

Stetson (1951) observed what he thought was evidence of temporal patterning of certain respiratory muscle contractions associated with syllables. While more recent investigations do not seem to confirm some of Stetson's original conclusions, there is an increasing amount of electromyographic data (for example, Lebrun, 1966) that reaffirm the presence of respiratory muscle contractions which may be uniquely associated with units of the speech signal.

When viewed from this perspective, it seems possible to contend that the neuromuscular process which operates to produce speech is not only a fantastically complex process, but it may well be dissimilar to other neuromuscular processes involving identical muscle groups. Some support for this position is now available from research with neuromuscularly handicapped speakers. Hixon and Hardy (1964) have reported that rates of syllable repetition show much higher correlations with the severity of the speech problems of a group of dysarthric children (athetoid and spastic quadriplegics) than do rates of simple repetitive tongue, lip, or jaw movements. Moreover, the interrelationships among rates of repetition of different syllables were much stronger than among rates of nonspeech movements (for instance, lateralization of the tongue). Amazingly similar results have been obtained with similar subject populations by Murphy (1966) and Smit (1969). In addition, among a number of physiological variables studied, Canter (1963, 1965a, 1965b) found that rates of syllables repetition were most strongly related to the severity of the speech problems of his subjects with Parkinson's disease, and Smith (1964) also found such rates produced by subjects who had Parkinson's disease to be significantly correlated with the severity of their speech defectiveness, while rates of tongue, lip, and jaw movements were not. These results strongly suggest that even in the presence of some type of abnormality of the neuromuscular systems, the speech-generating neuromuscular process is uniquely organized and is dissimilar from such processes that underly movements of the same muscle groups during other acts.

Another example supporting a unique organization of the neuromuscular processes for various types of activities may be found in the review of processes of mastication and deglutition by Fletcher in this *Report*. He cites the work of Kawamura and Kamada (1967), who found that emission of swallowing and phonation can be differentially produced via cortical stimulation with dogs.

Paillard (1959) discusses the motoneuron arrangements that may make possible the organization of quite dissimilar sensorimotor nets for different types of acts by the same muscle groups. He points to the elaborate somatotopic arrangements of the efferent neurons in both the cortical motor areas and groupings of cell bodies in the final common pathway, and suggests that through elaborate internuncial arrangements these efferent mechanisms may be so organized that each type of activity is emitted by a different neural pattern.

Neural Maturation and Learning

In 1959, Galambos and Morgan discussed the distinction between the processes of neural maturation and neural learning. Among other manifestations of neural maturation is the organized primitive behavior of the neonate and infant. Much of this behavior can be described as resulting from evolution of survival mechanisms (for example, the sucking reflex) or phylogenetic retention of acts of lower forms of life (for example, primitive postural reflexes). Such behaviors seem to be the result of some predetermined specificity of afferent systems, efferent systems, and their interlinking systems, along with the autonomic nervous system.

On the other hand, there is the arrangement, or rearrangement, of neural networks that result from responses of the organism to its environment. As those responses are learned, and the underlying neural mechanisms are established, it is said that neural learning takes place. Obviously neural maturation affects neural learning and vice versa, but, also, prime determinants of neural learning appear to be the constructs of attention and motivation mediated by the limbic and reticular systems.

Human neonates cry in response to noxious stimuli and deprivation. They also produce vocalizations. Even deaf infants vocalize for some time in a manner similar to hearing infants (Chase, 1968). This behavior seems to possess some of the unique characteristics of the fully developed sensorimotor speech process. That is, the musculatures of respiration, phonation, and the oral-facial complex are brought into coordinated action to produce such vocalizations. In addition, it has characteristics of a predetermined organization of a sensorimotor system in that it is a common behavior of newborn humans which appears to be organized prior to birth and is functional at birth.

Galambos (1967), in a later discussion of neural learning, suggests that the dichotomy between neural maturation and neural learning is less distinct than he believed in 1959. He suggests that some systems originally organized via maturational processes become elaborated through neural learning. Therefore, it may well be that primitive infant vocalizations represent the initial organization of the sensorimotor systems for speech production.

Development of Error Detector Systems

Much of the literature indicates that vocalizations of infants and young children can be reinforced through exposure to speech in such a way as to bring about changes in characteristics of the acoustic signal they produce. Staats (1968), in reviewing this information and presenting results of his own work, suggests that at least two variables are requisite for speech-learning: (1) reinforcers that will motivate the young child to reproduce the characteristics of the speech signal presented to him, and (2) the child's ability to discriminate among the characteristics of that signal so he can "match" his productions with the many subtly different speech elements he hears from others. Thus, the prime error-detector system involved in speech-learning seems to be the auditory process.

It has been established for some time that the auditory discrimination of speech events improves as a function of age (for example, Templin, 1957). Therefore, it might be said that the auditory error detector has relatively wide limits initially. However, as a function of learning, those limits become progressively more narrow.

It is difficult to contend that tactile-proprioceptive impulses enter into initial speech-learning to a significant degree as an error-detector system. This would require evidence that the nervous system of the young child has the tactile-proprioceptive patterns associated with speech production available for the matching operation before his sensorimotor system has learned that muscular behavior. This possibility does not seem likely.

It seems more likely that, as the muscular patterns become more precise during speech-learning, the tactile-proprioceptive networks eventually develop into error detectors and, thus, a coordinating system. That is, as the sensorimotor system improves its ability to reproduce the signal that its auditory error-detecting system is perceiving, the tactile and proprioceptive patterns become more restricted and, thus, learned through the less variable muscular behavior. Eventually, then, those tactile-proprioceptive patterns will become relatively fixed as the precision of the speech-producing musculatures stabilize. Chase (1968) reviews a series of researches suggesting that the effects upon speech of delayed auditory feedback increase as a function of age in children. Such findings support the suggestion that even though the auditory target is temporarily displaced in the young child, the tactile-proprioceptive comparator has such wide limits of acceptance that muscular function is minimally disrupted and, as speech-learning takes place, the limits of such acceptance of that comparator become more stringent. If such a possibility is tenable, the tactile-proprioceptive error-detecting system also would have relatively wide limits of acceptance in the initial stages of speech learning, and those limits would become more stringent as the speech production process is learned.

These suggestions imply that as the specialized sensorimotor patterns for speech generation begin refinement from crude patterning exhibited by infant vocalizations, there exist two error comparators with relatively wide limits of acceptance as to signals that are on target. However, those comparators narrow their limits of acceptance as a function of improved discrimination and learning.

This type of development of error-detecting systems would permit the development of defective speech skills for a number of reasons. If, for one example, auditory discrimination is defective and the child consequently is matching the output of his speech mechanism to the defective auditory signal that he perceives, the tactile-proprioceptive systems would develop monitoring patterns comparable to the inappropriate articulatory patterning. For another example, if some type of structural defect of the oral cavity does not permit development of normal articulation, the error-detector systems could come to accept the inappropriate target positions as the correct ones as neural learning takes place. Hence, the system can continue to run even though the output will be defective.

Interaction of Tactile-Proprioception and Somesthetic Sensations in the Developing System

It has been implied earlier that the tactile-proprioceptive systems involved in speech production are more interrelated with somesthetic sensory systems in the young nervous system than in the older, more fully developed system. This suggests some type of physiological interaction between those systems, initially, that does not exist after development.

There may be another explanation for this apparently detrimental effect upon speech development of abnormal oral somesthetic capability. By reviewing phylogenetic evolution of sensorimotor systems, Paillard (1959) suggests that the degree to which an animal will develop highly precise, complex movement patterns of given muscle groups can be predicted by the relative portion of the animal's cortical sensorimotor strip devoted to innervation of the muscle groups. In man, cell bodies associated with the function of the hand and face muscles, and particularly the oral musculatures, occupy proportionately large areas of the precentral gyrus area than do cell bodies that lead to innervation of other muscle groups.

According to Paillard, this rich innervation of hand and oral-facial complex muscles is, at least in great part, the basis for man's great capacity for developing precise complex movements of those muscles. He defines such movements as being different from more gross muscle patterns such as those associated with ambulation. He further suggests that these fine skilled movements, including those associated with speech production, require conscious effort for initial performance. However, as these movement patterns are learned by the nervous system, they become entrusted to sensory modalities for their control.

If Paillard's reference to conscious effort implies use of all possible sensory sensations to guide the muscle patterning during initial neural learning, it may be that integrity of the somesthetic capabilities of the oral structures is necessary for learning muscular patterns of speech production. In the absence of such integrity, the sensorimotor systems of those structures may be incapable of, or have difficulty in, learning appropriate patterns.

Paillard's comments about such movements becoming entrusted to afferent systems for control can be interpreted to mean there is a transfer from the somesthetic sensory systems to the tactile-proprioceptive systems, for regulation, as neural learning takes place. If so, there seems little need to suggest a difference in the physiological relationships of the tactile-proprioceptive and somesthetic systems as a function of development. Rather, the patterns of tactile-proprioceptive impulses along with the resulting discharge of cerebellar influence upon muscular systems may become established through initial use of somesthesia as a guidance system.

This suggestion seems compatible with the discussion on development of error-detecting systems since stereognosis of the oral cavity has been shown to improve with age (McDonald and Aungst, 1967). It seems conceivable that if somesthetic sensations are a part of the early "guidance systems" for speech production, those sensations come to have more precise discrimination capabilities and, in fact, contribute to the developing precision of speech musculature activity through improved discriminatory capability. Moreover, such an involvement of somesthesia in initial learning of speech musculature patterns would explain what appear to be problems of speech-learning associated with congenital somesthetic deficits.

Development of the Command and Storage Systems

The way in which the command system that drives the total speech producing mechanism develops must be pure conjecture at this time. In some manner the central nervous system stores, or learns, a set of phonological rules in terms of muscular patterns. From this storage system, or memory bank, the command system selects the appropriate set of muscular patterns for a given utterance. Current knowledge is too limited to provide much insight about the anatomy or physiology of these systems.

A review of the literature dealing with communication disorders resulting from damage to the nervous system helps very little. Only two general types of such disorders seem applicable to the current topic, namely the dysarthrias and what are beginning to be defined as speech apraxias. The dysarthrias appear to represent a disruption of output systems generally, and the speech apraxias are only beginning to be described definitively (for example, De Renzi, Peiczure, and Vignolo, 1966).

Cortical stimulation experiments, such as those by Penfield and Roberts (1959), have resulted in crude vocalizations or disruptions of speech muscular processes, but, as those authors state, the externally applied electric signal cannot be conceived as resembling in any way the intricate innervation from a variety of internal sources in the functioning system.

Penfield (1954) has suggested what he calls a centrencephalic system as a subcortical system that selects from storage systems appropriate muscular responses. This theoretical source of volitional movements is a physiological concept in that the total anatomical structures of which it is composed are not specified. To the extent that such a concept has validity, the portion of it dealing with emission of speech generation may represent the command system.

Further delineation of these storage and command systems may depend upon elaboration and refinement of the theoretical models of the speech-producing systems. Elsewhere in this *Report*, Ringel has implied that current evidence does not permit firm acceptance of any one such model over others, and I agree. However, it may be most profitable to approach further development of such models in line with what is understood regarding neurophysiology of the sensorimotor systems underlying speech generation and their development.

CONCLUSION

A statement has been made that attempts to fit many, sometimes fragmentary, pieces of information into the very large puzzle of how the neuromuscular processes underlying speech generation develop their function. Because of the broad nature of the material covered, few suggestions for specific research endeavors have been stated. However, every qualifying term such as "it seems" or "suggests"—and there are many—implies a need for more definitive information. Contradictory evidence exists to some of the interpretations offered, and to that extent the statement may need revision. However, from the vast array of research, clinical observations, and relevant theories, those have been chosen for reference that fit into a framework that seems reasonably cohesive. Such a framework should provide for a systematic approach to further research.

Among the issues raised, there are obvious ones that need resolution through research. The variety of professional interests and backgrounds that must be brought together to accomplish that resolution is great. For only one example, it is still uncertain what specific peripheral mechanisms contribute to tactile-proprioception and somesthesis. Definitive resolution of that issue may assist substantially in answering such questions as whether or not, and if so how, abnormal functioning of those mechanisms contribute to a speech-learning problem.

Other issues raised appear to have immediate clinical implications. If it can be determined that the sensorimotor systems underlying speech generation are, in fact, uniquely organized and dissimilar to those of deglutition, a better understanding of deficiencies of the various functions of the oral-facial complex may be obtained, and, more importantly, clinical management techniques may be made more efficient.

Because the systems involved are so complex, resolution of such issues will not be simple. Nevertheless, concerted multidisciplinary approaches should be able to make substantial progress.

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SPEECH ARTICULATION AND ORAL MORPHOLOGY

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For the last two decades researchers in speech science and dentistry have focused on the relation between speech and oral morphology. The many attempts to delineate this relationship have not been definitive. It does, however, appear that the shape of the oral structures must have some significance for speech performance. Other papers in this *Report* describe the neurologic, muscular, and skeletal systems subserving language acquisitions, speech development, and performance. These provide a basis for discussion of the morphological aspects.

At the outset we may distinguish among several general frames of reference in which oral morphology and speech can be considered:

1. Irregularities in both speech and oral morphology may develop independently, but appear concurrently by chance. The probabilities of such chance concomitance are suggested by the fact that dental malocclusion is observed in as many as 50% of the children in certain populations, while deviant speech may occur in 10%.
2. Developmental abnormalities may result from genetic or early metabolic disorders which affect the central nervous system and which are expressed in deviant behavior and distorted morphogenesis. For example, Mongolism reflects a genetic disarray, and cerebral palsy may ensue from metabolic trauma.
3. Deviant shapes of the jaws, palate, and dental arches, or anomalous postural positions of the jaws or lips deleteriously affect articulatory skills, even though a very efficient neuromuscular speech mechanism may be present.

Germane to the first postulation, coexistence, is Bloomer's (1957, 1963) comprehensive review of the literature and discussion of the various aspects of speech and dental malocclusions. He concludes that malocclusions occur more frequently in children with defective speech than in children with normal speech. This establishes a closer relationship than that which could be due to chance alone.

Several authors have described the second possibility, deviant morphology associated with genetic and metabolic disorders (Cohen and Winer, 1965;

Isshiki, 1968; Kastein, 1957; Rosenbaum, McDonald, and Levitt, 1966; Russell, 1969; and Spitzer, 1967). The comparative significance of deviant oral morphology in relation to speech is difficult to establish in those pathologic conditions involving the central nervous system, since relevant methods of assessment are as yet unavailable. However, an analysis of the symptoms is helpful in determining hypotheses for future research.

The frequent return to the problems raised by the third formulation demonstrates the need for further information on the effect of deviantly shaped jaws and dental arches on speech. Research has produced some insights. For example, in 1951 Fairbanks and Lintner observed that variation in palate form was not significantly related to articulatory proficiency. The study was limited to 60 young adults and apparently did not include any with abnormal palates. According to these findings, it appears that tongue movements readily compensated for variation in palate form, and the central part of the hard palate was not a significant aspect of the speech articulation system. They observed that dental deviations were significantly more numerous among the individuals with inferior articulation. An open bite in the incisor region was considered particularly important.

With respect to this last factor, it has been noted in the orthodontic literature that an open bite in the incisor region occurs in conjunction with several conditions, such as finger sucking, deviant swallowing habits, large tonsils and adenoids, mouth breathing, macroglossia, and micrognathia. Also frequently mentioned is the association of macroglossia with a slow diadochokinetic rate and speech disorders. Some open bites may be caused by large and slow-moving tongues which perform inadequately during speech. In other instances, the tooth position may be distorted by factors such as the presence of fingers in the mouth, and the speech mechanism is left with a handicapping structure. A clear distinction between these two categories is essential for the interpretation of research findings.

In 1957 Benediktsson used cephalometric x rays to study the position and movements of the tongue and the mandible during the production of the /s/ phoneme in 246 subjects. The group included individuals with normal occlusion and those with an abnormal position of the incisors. The results indicated that the incisor relationships had a marked influence on the movements and the position of the tongue. It was observed that compensatory variations of jaw and tongue movements frequently resulted in a normal relation of tongue tip to teeth during /s/ production. In persons with extreme maxillary overjet or severe overbite, there was a tendency toward a forward movement of the lower jaw. With open bite, the forward movement was very slight in all groups. Regardless of the degree of overjet, a pronounced lowering of the mandible occurred with severe overbite or deep bite.

The Benediktsson study demonstrated that precise control of tongue movements may be difficult not only in the presence of an open bite, but also with large overjet and overbite. Specific movements of the mandible, usually not involved in speech articulation, may be required to bring the tongue into the proper position for /s/ production. The significance of this observation probably is not appreciated fully at the present time; the facilitation of the neuromuscular systems of mastication, facial expression, and respiration for serving and supporting the speech mechanism is recognized but not clarified.

Ward et al. in 1961 investigated the relationships among dental occlusion, swallowing, and tongue-tip sounds. Their findings revealed a relatively high incidence of disorders in the 358 subjects; namely, visceral swallowing in 75%, malocclusion in 47 to 65%, and articulatory variations in 64%.

In 1962 Ingervall and Sarnas studied dental occlusion in a group of lispers who were paired with nonlispers as controls. A distinction was made between interdental and lateral lisping. The dental occlusions among the lispers differed from those of the nonlispers. However, no information was provided regarding factors underlying the superficial symptoms.

Normal and abnormal production of the /s/ phoneme was investigated by Subtelny, Mestre, and Subtelny in 1964. Finding that tongue thrust and malocclusion coexisted with normal as well as with defective speech, they concluded that "variable relationships existing between malocclusion, tongue thrust and defective speech indicate a need for carefully controlled research to objectify muscular behavior as it relates to specified structure during speech and deglutition." Jann, Ward, and Jann in a 1964 study on speech articulation, deglutition, and swallowing, stated that "it is difficult at this time to make generalizations concerning orofacial muscle behavior during the age level studied." Although their subjects were elementary school children, the statement could also apply to other age groups.

Work by Weinberg in 1968 focused on normal and defective /s/ articulation and variations in incisor position. His research showed that significant differences between normal and defective /s/ articulation were related to the environmental characteristics of the anterior oral constriction. Speakers with defective /s/ "excessively fronted the tongue tip."

Implicit in these foregoing studies, which were epidemiologic in design, is the need for reorientation in research approach. Additional accesses are necessary in order to penetrate beyond the observation that certain combinations of dental malocclusion and deviant speech articulation occur more frequently than others. Several issues emerge from the implications of the research surveyed herein.

First, questions may be posed regarding conventional classifications of dental malocclusion and also regarding the tests for assessment of speech articulation. Are these valid parameters?

The dental profession has established certain specific morphologic norms for both sexes at various age levels. These standards are based on linear dimensions, geometric proportions, and angles describing the relation between the jaws and the teeth in occlusion. This is obviously a static position—a circumstance which does not occur during speech. The identification and measurements of "open bites" and "incisor overjets" are established with the dentition held in this "solid state."

The notion of morphology, as employed in dentistry, may serve to distinguish between the child and the adult, the small and the large. It describes the variations in the shape of bones and the normal, slow changes in size which occur during growth and development. However, in speech these anatomical structures participate dynamically in the shaping of the vocal tract with its valves and restricted passages. It is, then, not the anatomical structures per se, but the spaces between them which are important. These spaces are created by movements of the jaws and dentition and by the changing configuration and movements of the cheeks, lips, tongue, palate, and pharynx. During speech the shape is not static, but dynamic.

Speech science has not always distinguished between the active changes in shape or morphology and the speech function. Thus the concept of oral morphology as a description of stable structures should not be accepted unequivocally, but should be considered in terms of its relevance to speech physiology.

From a dental viewpoint, the change in shape of the anatomical structures and the vocal tract is a product of function, just as the acoustic output during speech is a product of function. The dynamic, continuous changes in shape and the onsets, cessations, and modulations of the acoustic output are parallel phenomena created by the function of the underlying neuromuscular skeletal systems. Let us assume that in any language the articulatory movements of speech blend easily under morphologic conditions which are average or normal for the group. The shape and relative size of the jaws, the shape of the dentition, the palate and lips become significant factors when they inhibit the smooth synthesis of articulatory movements.

Illustrative of these relationships are severe incisor overjets, a typical anatomical feature which may affect speech articulation. As described by several investigators, the mandible must move forward when the overjet is severe, in order to carry the tongue to the position required for the /s/ sound. Muscle action not usually engaged in speech may be necessary for this movement. Thus, the neuromuscular system ordinarily underlying speech is strained beyond capacity. The neuromuscular function producing the sound is deviant, even though the acoustic output may sound normal. That is, a deviant neuromuscular action may move anatomically deviant structures, such as large incisor overjets, into a particular relation in order to produce an acceptable acoustic result. Under such specific conditions the acoustic output does not clarify the complex relationship between speech articulation and oral morphology; it merely serves to cover it. Acoustic output, therefore, cannot be accepted as a valid parameter unless the underlying neuromuscular activity is considered.

Further questions may be posed regarding the description and classification of jaw relations and dental malocclusion. Would the "postural position" provide a more valid basis for assessment than the "dental occlusion" position? The relationships between the jaws, lips, and teeth, and between the tongue and teeth may differ significantly in these two placements. The "dental occlusion" position is reached by active involvement of the masticatory muscles. Neither the changes in relative position of the anatomical structures nor the underlying neuromuscular activity which moves the mandible to this position has been considered in previous studies.

Information is available in many fields which can provide a basis for new research departures. A list of publications pertinent to this problem is provided. As a prelude, certain problems should be resolved. For example, the etiology of dental malocclusion is not completely apprehended. However, experimental work on primates indicates that open bites, incisor overjets, and deep bites will appear when normal dento-alveolar tissues respond to certain changes in the oral neuromuscular environment (Harvold, 1968). Such changes involve, for example, relative muscle tonus and posture, and tooth contact with adjacent soft tissue. Occasionally a deviant potential in tissue response is recognized as it is expressed in hypertrophic or hypotrophic conditions.

It seems justifiable, therefore, to assume that dental malocclusion in man may generally be produced by potentially normal oral tissues in response to deviant behavior of the orofacial structures. From this perspective, severe dental malocclusion may occur when a structure is highly responsive to changes in oral behavior. The identification of favorable and unfavorable oral behavior becomes essential and a method for assessment should be developed. As previously mentioned regarding speech articulation, the acoustic output does not convey the essential information. In order to reach the crucial information, a subject's general articulatory skill should be distinguished from the specific problems due to oral morphologic deviations. This dimension of oral behavior and the causes of dental malocclusion can be investigated at the same level.

Oral behavior is the sum of activities in the various neuromuscular systems subserving respiration, mastication, facial expression, and speech. The various motor control systems underlying these functions are highly integrated but with specialized areas and centers subject to complex priority regulations. Morphologically, the systems are delineated in considerable detail, but their function is still only fragmentarily described. The essential questions are: Which system is most influential in the morphogenesis of the orofacial structures, and which systems may support the speech mechanism in overcoming anatomical deviation?

The assessment of neuromuscular activity and differentiation among several integrative systems constitute a fascinating, albeit formidable, task for collaborative research in speech science and dentistry.

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MUSCULAR FUNCTIONS OF THE DENTOFACIAL MILIEU: SPEECH

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The function of muscles individually and collectively during the production of speech has continued to hold the attention of investigators in speech science, psychology, physiology, medicine, and dentistry. The literature on the subject indicates that the sublevels of speech production might be divided into motor commands at the neurological level, dynamics of muscular movements, and acoustic properties of the various sizes and shapes of the resonating cavities. Numerous descriptions are available regarding individual muscles and their actions during the production of specific speech units. These descriptions might be considered data necessary to know before attempting adequate theorizing. It is not my purpose to repeat these descriptions, but rather to attempt to summarize some of the information, and to discuss some theoretical constructs, applied to research on dynamics of muscular movements.

Other papers in this *Report* discuss the techniques available for acquiring information about the physical nature of muscles, their function, their innervation, and the skeletal framework that forms their supporting structures. Therefore, my primary focus will be on the function of muscles during the production of speech, with attention to pulmonary influences on laryngeal, upper pharyngeal, and upper articulatory events. Emphasis will be placed on the way in which movements of various muscle groups of the speech mechanism act on the egressing breath stream to modify it into specific speech units. Secondly, some attention will be given to the role of muscle function in speech production as it may be involved in the perception of speech, the serial ordering of speech, and the feedback mechanisms monitoring speech. Information about developmental changes in dynamics of muscle function will be included whenever possible.

PULMONARY INFLUENCES

The importance of the respiratory process and the pulmonary functions associated with it are readily apparent if one accepts the following idea put forth by Peterson (1968):

> While the production of sound in the vocal mechanism always involves the movement of some part of the system (e.g., the respiratory muscles), the sound is not normally produced by the transfer of energy from some moving anatomical part to the air con-

> tained in the vocal tract. Rather, the air flow is controlled by the vocal mechanism and it is this air flow which excites the sound. For example, in the production of /s/ with a pulmonic air mechanism nothing except the air moves at the place where the sound is generated.

This hypothesis lends support to the current research that attempts to show that relationships do exist among parameters of volume of air flow, oral and nasal breath pressure, and physiological events.

Although the mechanism for producing the sounds of languages is actually an integration of parts of systems for processing food and for respiration, actions used in sound production differ considerably from actions of the same mechanism used in chewing, swallowing, and respiration for life purposes. Vocal-fold actions utilized in protecting the lungs from foreign objects are quite unlike those vibratory cycles observed during the production of speech sounds. Although the life processes of the mechanism are of interest to the speech pathologist, study of them may or may not reveal information that is transferable to speech production movements.

The speech mechanism may be considered as a sound-generating source and a set of filters that act on the sound. Physiological events may change the size and shape of the vocal tract to produce the filtering effects as sound egresses with the breath stream. According to Peterson and Shoup (1966), the speech mechanism is capable of acting on the breath stream in a number of ways, namely: air mechanism, air direction, air flow, air release, air pressure, general air path, and lingual air path. All of these are the result of the interaction of muscle groups rather than of single muscle function and interference with one of these respiratory parameters is likely to cause interference with another. For example, in cases of palatal insufficiency there is an inability to control the general air path and direct it nasally or orally as needed. In the presence of this problem, the rate of air flow is increased during consonant production (Warren, Wood, and Bradley, 1969). It is hypothesized that the increase in air flow is related to attempts to increase intraoral pressures to the levels necessary for adequate production of consonants.

Woldring (1968) has demonstrated basic problems in control of expiration during speech of deaf children. Pneumograms indicated marked deviations in the control of expiration and five to eight times more inspirations for the deaf children. He attributes the deviant patterns to lack of auditory feedback rather than to any muscle deficiency, and he has improved speech patterns by providing tactile feedback through vibrations on fingertips.

It is fairly well accepted that maintenance of any given subglottic pressure during air flow is accomplished by a neatly adjusted balance between the elastic forces of the inspiratory muscles (usually intercostals) and the expiratory muscles (usually abdominals). The classic work of Stetson (1951) indicated direct relationships between action of respiratory muscles and the release or arrest of specific phoneme units at the syllable level, leading to the development of a motor phonetic theory. Even though some subsequent work (Hoshiko, 1960) does not support all of his findings, the importance of the work remains. A current investigation (Suzuki and Kirchner, 1969) suggests the important addition of the posterior cricoarytenoid as an inspiratory muscle. Thus far, the physiologic phonetic theory of Peterson and Shoup (1966) proposes that pulmonic air mechanism is involved in production of all speech sounds, and the participation of other mechanisms has not yet been identified. In considering the pulmonic air mechanisms, one should remember that the number of alveoli increases tenfold from birth to adult status, with more than half of the increase occurring during the first 13 months of life. Essentially the same situation exists for number of airways and body-surface area of the lungs. The air-tissue interface area increases 21-fold between birth and adulthood. Establishment of patterns of muscle movement controlling pulmonic pressures occurs against this background of maturation in lung size.

With the exception of the Woldring study (1968) reporting on deaf children, and Hardy (1967) on cerebral palsy patients, most of the research on respiratory function in speech has been on adult subjects. It is extremely important to consider the appropriateness of known techniques to a study of the developing mechanism and to replicate studies on adult subjects with child subjects of several age levels. To study the disorders of speech is equally important, since theories of normal speech production may be verified by adequate understanding of deviant speech patterns.

The direction of the air stream is assumed to be always egressive during the normal production of speech sounds in English. However, clinicians have seen persons with speech disorders produce speech (such phonemes as /s/, /z/, /θ/, and /ð/) on ingressive air. In a radiological study of the larynx, Passaglia and Tassini (1966) have described inspiratory phonation. This phenomenon is probably not of prime importance with regard to English, except to recognize that the speech mechanism is indeed capable of acting on the breath stream to initiate phonation on inspiration. Children have been observed speaking on inspiratory breath streams as a game. Such speech is intelligible but quite short phrases are used.

Rate of air flow through the nasal cavity and the oral cavity has been the subject of much research, which is being discussed elsewhere in this *Report*. Except for laryngeal valving, muscle function related to controlling the rate of air flow will be discussed herein more directly, as articulatory placement.

LARYNGEAL INFLUENCES

The larynx is considered to be the first level in the vocal tract at which constriction occurs to impede or control the flow of air from the lungs. Some authors (Peterson and Shoup, 1966) suggest nine different actions of the laryngeal muscles resulting in four states of air flow. In addition to controlling the state of the air flow, these laryngeal actions are thought to release the air in five different manners.

When the vocal folds function to protect the lungs they need only close forcefully or open widely. "Opening is accomplished by the action of one pair of muscles (the posterior cricoarytenoid) sliding the posterior attachment of the cords (the arytenoids) laterally. Closure results from the contraction of the lateral cricoarytenoid and interarytenoid muscles" (Proctor, 1968). This rather simple description of function in valving can be contrasted with the following description of laryngeal muscle function during phonation as stated by Zemlin (1968):

> The exact relationship between muscular contraction and laryngeal behavior is not known with absolute certainty. A subtle, delicate interplay of the various muscle actions produces the appropriate movement. In adduction of the vocal folds, contraction of the interarytenoid muscles may draw the muscular processes posteriorly, thus toeing out the vocal processes. Although the arytenoid muscles are classified as adductors, in this case they are actually abducting the vocal folds. On the other hand, when the lateral cricoarytenoid muscle is contracted, the arytenoid cartilages are rotated so that the muscular processes are pulled anteriorly and the vocal processes toed inward to produce the glottal configuration required for production of a whisper. Simultaneous contraction of the lateral cricoarytenoid and the interarytenoid muscles approximate the arytenoid cartilages and the vocal folds so that their medial borders are parallel. Such muscle action, however, may also draw the arytenoid cartilages forward, a movement that is restricted by the antagonistic action of the posterior cricoarytenoid muscle. The result of the activity of the three muscles is such that the vocal folds are rather tightly approximated and if exhalation is initiated while the vocal folds are adducted, they are set into vibration to produce a laryngeal tone. Needless to say, there is a direct relationship between the extent of adduction, or medial compression, and the amount of air pressure required to force the vocal folds apart.

The contrasts in the complexity of laryngeal functions for phonation and for simple valving thus are apparent. Changes in pitch provide an example of muscular movements involved in changing the length of the vocal folds (Hollien and Moore, 1960). Three or four laryngeal muscles are responsible for adjustment of the vocal folds to effect changes in vocal intensity (Isshiki, 1964; Charron, 1965).

The function of the laryngeal mechanism appears consistent, even though the vocal folds almost double in length during the first year of life and increase in length from 3 mm at birth to about 17 mm for females and about 23 mm for males at maturity. I located essentially no reported studies of laryngeal function in young children. The need is tremendous for verification that functions present during the speech-acquisition years are the same as in adult function. Critchley (1967), for instance, observed that children before the age of three or four months are not able to modulate the voice in cooing. Clinically, it has been observed that instructions for children to increase the speed of syllable production results in increased loudness rather than speed.

Instrumentation for the study of intraoral pressure has made possible a number of studies that are of significance in providing indirect evidence of muscle function acting on the breath stream. Only one study will be mentioned, to demonstrate some possible advantage in shifting our analysis from the action potentials of specific muscle units to the effect of total muscle functions on the breath stream. Lubker and Parris (1970) recently completed a study of simultaneous measurements of intraoral pressure, force of labial contact, and labial electromyographic activity during the production of /p/ and /b/ in various phonetic contexts. They concluded that intraoral pressure provides good /p/ . . . /b/ discrimination while labial pressure and EMG activity both provide equally poor discrimination.

The remaining ways in which the speech mechanism acts on the breath stream including general air path and lingual air path will be discussed in later sections of this paper.

PHARYNGEAL INFLUENCES

Participation of the upper pharynx in production of speech sounds continues to be somewhat neglected in research efforts. Basmajian (1967) has offered the explanation that the striated muscles of the pharynx are relatively inaccessible. Fletcher (1958) describes rather abrupt sphincteric movement of the entire wall incident to crying in infants. Initiation of activity in the upper pharynx seems temporally related to tactile stimulation by a food bolus or contact with the soft palate. Maturational modification is thought to be represented by cessation of sphincteric action during phonation except in instances where a discrete transverse bar or ridge develops on the posterior pharyngeal wall. Commonly known as Passavant's pad, the importance of this discrete function has been debated at considerable length. Fletcher (1958) reported its presence in 3 of 10 normal speakers and in 9 of 10 hypernasal speakers. It is observed more frequently in persons with palatopharyngeal insufficiency. Calnan (1954) questioned the significance of such a ridge. The development of cineradiographic and ultrasound techniques has provided instrumentation for study of medial movement of the lateral walls of the pharynx accomplished by the salpingopharyngeus muscle. Most research attention has been focused on muscle movements that narrow or constrict the pharynx. Recently, Rothenberg (1968) has noted the function of the inferior pharyngeal constrictor and the stylopharyngeus in expanding the dimensions of the pharynx. The action of these muscles, coupled with movement of the base of the tongue and forward motion of the larynx, results in a projected volume change of about 6.0 cc of air. Although such changes in volume capacity in the pharyngeal area may seem small, this finding has numerous implications regarding transglottal air flow.

The cricopharyngeus muscle in its normal function is thought to be of little importance in the production of speech. However, in the case of the laryngectomized patient, it may function as a pseudoglottis. Diedrich (1968) describes its various functional capabilities in this regard in some detail.

Although syllables of the English language are not customarily produced by any constriction of the oral or laryngeal pharynx, Subtelny (1968) has observed such constrictions or attempted constrictions in individuals who have palatopharyngeal incompetence. When such constrictions are attempted, movements of the base of the tongue differ markedly from the positions assumed in the production of accurate English phonemes when palatopharyngeal function is normal.

The action of the soft palate in directing the air stream orally or nasally has probably received more attention than almost any other articulatory function.

The vigorous research efforts of investigators involved in the clinical management of individuals with repaired cleft palate and other palatopharyngeal insufficiencies are largely responsible for the body of knowledge available.

Vocalizations of infants below three months of age tend to have a nasal quality. This appears to be the result of a phonatory stream that is allowed to egress through oral and nasal cavities simultaneously. During postnatal maturation of the facial skeleton the palate is anatomically displaced ventrocaudally, thus creating space for mobility. Palatal activity in the infant is crudely in a cephalic direction and does not modify until the craniovertebral angle is acquired by the ventrocaudal migration of the bony part of the palate, according to Bosma and Fletcher (1961).

As the soft palate descends in relation to the origin of the levator veli palatini muscle, the function of the levator changes from that of tensing to one of elevating the palate. The descent of the hard palate is relatively greater than that of the hamular processes and, as this descent is complete, the tensor veli palatini no longer acts as a depressor of the palate but becomes a palatal elevator.

During development, the palate is anatomically elongated and achieves a position of stabilization within the pharynx by balanced activation of its suspensory musculature, including the levator, the tensor, and the palatopharyngeus. As this occurs, the pattern of crude arching during movement toward the posterior pharyngeal wall is replaced by a definite knuckled or foot-like contour at the middle third of the soft palate. Bosma and Fletcher (1961) report that the distal portion of the soft palate remains free and often does not participate in contact with the posterior pharyngeal wall.

Palatopharyngeal closure in children appears to be accomplished with a primarily posterior movement of the palate in which a broad mass of the palate touches the adenoid tissue and pharyngeal wall. In adults palatopharyngeal closure usually results from the posterior and superior movement of the soft palate to achieve apposition to the posterior pharyngeal wall at a more discrete location. This information on the changes in direction and nature of movement of the soft palate in separating the nasal cavity from the oral cavity and thus directing the breath stream is one of the few instances in which developmental information is available.

Fritzell (1969) has recently written one of the most comprehensive accounts of soft palate action during speech. He concluded that, in adult subjects, the movements of the soft palate follow very closely the activity of the levator muscle. The palatoglossus does not seem to control the soft palate except in lowering it for production of nasal sounds. Even then, the lowering action does not occur before action of the levator has ceased. He reaffirmed the findings of others that the palate achieves higher elevation for high vowels such as /i/ than for low vowels like /u/. Velar movements were initiated about 40 msec after the onset of levator activity. Speech sounds followed in about 300 msec. There was considerable variation in the onset of speech sounds.

Controversy continues to exist in this area regarding the degree of closure necessary to direct the air stream orally. Several recent EMG studies (Lubker, 1968; Fritzell, 1969) indicate that the muscles of the soft palate contract to produce a number of intermediate velar positions. It is feasible that further investigations might demonstrate four or more basic velar positions roughly comparable to the four modes of general air path postulated by Peterson and Shoup (1966). Also, this might explain the lack of correlation consistently reported between palatopharyngeal closure and severity of hypernasality. As has been suggested before, the velar positions required to direct the air flow orally might be influenced by the height of the tongue and the degree of nasal resistance present. Further research is needed to determine the relationships that do exist.

UPPER PHARYNGEAL INFLUENCES

Considering all of the upper pharyngeal articulators, none is more facile or as well developed in its function than the tongue. Some actions of the base of the tongue have been mentioned already, but much more needs to be stated. Although the tongue is more mature than some other structures at birth, it nevertheless doubles in size before maturity. In function it is likely that it changes as much as any muscle group. At birth it almost entirely fills the oral cavity. The extrinsic muscles are oriented to move the tongue primarily in a horizontal plane. The intrinsic muscles which serve to control the finer adjustments of the tongue and enable it to sustain various positions are poorly developed at birth and extrinsic musculature is the principal determinant of tongue movement.

As the child matures, a greater variety of form and rapidity of motion is gained. Expansion of the oral cavity and maturation of the intrinsic muscles, along with the rapid elongation of the apex and blade of the tongue, contribute to rapid, more varied movements. The extrinsic lingual musculature then provides the important function of providing a stable postural background from which the intrinsic musculature may control fine, discrete movements. The tongue ceases to function as a whole organ and discrete movements replace the thrusting motions observed earlier. In essence, the tongue tip begins to function, independent of the tongue in general, to produce more discrete actions of elevation, and to form grooves to guide the air stream more efficiently. This increased ability to function allows a greater variety of motions associated with vowel and consonant production.

The transition from gross movements of the tongue to precise and finely controlled ones is gradual and extends over the first several years of the child's life. Fletcher (1966) provides a descriptive example:

> Acquisition of the /t/ and /d/ phonemes is characterized in the young child by a broad contact with a thrust like motion in which the tongue is rather crudely and indiscriminately approximated to the alveolar ridge and maxillary dentition. In mature speech this movement consists of a deft, rapier like movement of the tongue tip against the alveolar ridge easily released and facilitated by a poised reciprocity of the tongue proper.

Another example is the frequency with which any elevation of the apex of the tongue is accompanied by upward movements of the mandible in the young child. The mature speaker has the ability to elevate the apex of the tongue independent of mandibular action.

Much more information is needed about the developmental aspects of tongue function. In the presence of relatively little data, Mol (1965) has suggested that the child learns to master the muscular activity necessary for producing the same number of perceptibly different vowel sounds used for coding purposes by adult speakers of the same language. Once settled in a certain period, believed to be before the tenth year of life, the neurological programs for controlling the articulatory muscles do not change appreciably. Apparently the tongue keeps the same relative position in the vocal tract for each vowel. Lengthening of the vocal tract causes the vowel formants to shift downward and the speaker does not appear to engage in compensatory movements to maintain the original higher formants.

Houde (1967) recently reported the results of a cineradiographic study of tongue movements involved in CVCVC syllables. For the speech sample used and the few speakers studied, he reported several principal findings: (1) The vowel targets were influenced by stress and phonetic environment. (2) Vowel targets in the environment of /g/ as compared to the environment of /b/ differed by a "few" millimeters. (3) The time course of the transition of an articulatory element from one target position to the next was determined entirely by the distance between the targets and was independent of the direction and timing of the targets. (4) Unexpected perturbation components of tongue motion were observed. This study because it is one of the few that have investigated the motion of the body of the tongue.

One other study should be mentioned in relation to the movements of the tongue in articulation, and that is the work of Perkell (1969). He concluded from a cineradiographic study of articulatory movements that the tongue apex is more active in consonant articulation, while the body of the tongue is active in consonant and vowel articulation. The rationale utilized to explain this is the hypothesis that vowel production is accomplished by the larger, slower extrinsic tongue musculature while the smaller intrinsic musculature is responsible for the more precise, more complex and rapid actions necessary for consonant production. Further discussion of the evidence for categorical function of the articulators will be presented a little later.

The final structures to be discussed as upper articulators are the lips. Fletcher (1966) again provides some suggestions regarding the maturational aspects of lip function. Early in life, infants show the ability to round the lips in the suckling and rooting reflexes. Motions are directed medially, suggesting that early movements in speech will demonstrate medial focus and will progress simultaneously toward the lateral peripheries. The most prominent sound in infant vocalization is /a/, which places no demands upon labial participation. The next vowel acquired is /u/, followed shortly by /i/. These vowel productions are developed during the first few months of life. Central, contrasted with lateral focus of labial movements is one of the principal physiological differences among these three vowels. Little additional differentiation of lip movement develops.

The degree of lip protrusion is thought to be a significant factor in varying the length of the vocal tract. The lips do form the last area of constriction or complete stoppage of the egressive breath stream during the production of consonants. Several investigators (Harris, Lysaught, and Schvey, 1965; Malecot, 1966; Lubker and Parris, 1970) have utilized EMG for determining activity levels of lip musculature in studying bilabial voiced-voiceless contrasts. Findings are not consistent and appear to be subject to considerable variability. However, evidence appears to be leading toward the conclusion that the lips function to achieve closure irrespective of phone type.

From the foregoing discussions it should be apparent that the major research emphasis with regard to muscle function in speech has been directed toward a descriptive account of movements associated with sound production. Approached from this viewpoint, the sequencing of various movements, overlap of movements, simultaneous action of numerous muscle groups, and inability to isolate specific muscle units present an analytical task of enormous complexity. It is for this reason that I suggest that it might be profitable to shift our emphasis from specific muscle action to effects on the breath stream which result from the total involvement of all participating muscles along a time continuum. (See Rothenberg, 1968; Peterson and Shoup, 1966; Cavagna and Margaria, 1968.)

SPEECH PERCEPTION

The role of muscle function in speech does not end with the parameters involved in the production of specific phonemes but rather is thought to extend into such areas as the perception of sounds, serial ordering of speech, feedback mechanisms regulating speech production, and speech synthesis activities. Information on some of these topics is presented elsewhere in this *Report*. The limited scope of the following discussion is not likely to overlap such material to any great extent and should serve to emphasize the complexity of muscle function in speech production.

In the late 1950s and early 1960s, some experimental work at Haskins Laboratories was directed toward the identification of the generative and articulatory rules that would aid in the production of speech by synthesis (Cooper et al., 1958; Liberman, 1957; Liberman et al., 1962). Many of their efforts were based on the assumption that the sounds of speech perceived by the listener are perceived by reference to the way the listener generates that particular sound when speaking (Liberman et al., 1964). Lieberman (1967) later indicated that the motor theory pointed to strong connections between the acoustic and articulatory aspects of speech, with the concept of phonologic features representing optimal coding of the articulatory and acoustic levels of description. He interpreted his own research data as suggesting a close relationship between the inherent properties of the speech output mechanism and the perceptual recognition routine with regard to intonation and stress.

More recently, some controversy has arisen regarding the motor perception theory of speech, and such authors as Lane (1965) and Denes (1964) have questioned the theoretical constructs underlying this theory. They reported data that failed to support it. More crucial, perhaps, is the current position of MacNeilage (1969), who describes one of the limiting factors of the theory as being the lack of a direct relationship between the acoustic signal and the EMG correlates. The relationships were very close for vowels but not for consonants. Although the Haskins group indicated some awareness of this situation very early, they did expect to identify a core of invariance at the electromyographic level based on the hypothesis that invariance does exist at some articulatory level, possibly the level of motor commands that activate the articulatory muscles.

The following statement by MacNeilage (1969) summarizes clearly the present status of research related to this problem of invariance:

> Paradoxically, the main result of the attempt to demonstrate invariance at the electromyographic level has not been to find such invariance but to demonstrate the ubiquity of variability. For example, MacNeilage and DeClerk (1969) found that in an inventory of 36 consonant-vowel-consonant monosyllables, some respect of the motor control of every phoneme differed in some aspect depending on the following one. It is easy to understand, a priori, why the motor correlates of a phoneme would differ according to the identity of the previous one. Each phoneme, by definition, requires a unique constellation of articulator positions. Therefore the sum of the mechanical demands in achieving a second phoneme positioning will necessarily vary with the identity of the preceding phoneme. It thus appears likely that some aspect of the motor control of the 44 (Denes, 1963) phonemes of English will vary depending on which of the approximately 20 possible phonemes precedes or follows it. This gives a total of approximately 17,000 motor patterns without considering stress effects, speaking rate effects, and segmental effects which stretch across one or more phonemes, as does lip-rounding on some occasions (Kozhenvikov and Chistovich, 1965; Daniloff and Moll, 1968).

MacNeilage (1969) goes on to conclude that "the essence of the speech production process is not an inefficient response to invariant central signals, but an elegantly controlled variability of response to the demand for a relatively constant end."

Irrespective of the current reconsideration of the "invariance" aspect of the motor theory of perception, it has been found useful in explaining the acquisition of motor function in speech. Chase (1968) thus indicated that the ability to speak a language requires the learning of a finite set of motor organizations of the vocal tract, which, when appropriately excited, gives rise to the basic set of sounds out of which the words of the language are built. He alluded to the problem of invariance in this explanation: "Implicit in the efficiency of the speech communication system are the rigid constraints that must be imposed upon the motor organization of the phoneme system . . . the constraints . . . arise against a background of plasticity that allows any human nervous system to learn any or several of a very large number of languages . . . ."

Although the "analysis by synthesis" model of speech perception proposed by Stevens and Halle (1967) differs from the motor theory of perception, it too utilizes the concept of internal comparison with sound-production movements. However, Stevens and Halle (1967) have proposed that as the listener attempts to perceive speech, he uses certain rules and matches internally generated patterns against the pattern under analysis. They believe this method of analysis follows rules which account for the distinctive features of the sounds of a language. The acoustical output then can be considered a joint function of the abstract representation, the rules of the language, and the dynamics of the vocal tract. The decoding into the abstract representation again follows the rules of segmentation and distinctive features. Applied to language acquisition, they argue that the child must learn the phonological rules rather than a set of motor skills.

SERIAL ORDERING OF SPEECH

Almost any discussion of the serial ordering of speech will involve neural mechanisms to the extent that it might best be considered in the neural mechanisms presentations in this *Report*. However, the end product of the neural commands is movement by the muscle units to which the command goes. A recent article in *Science* (Willows and Hoyle, 1969) reports the identification and location of neurons that appear to control a relatively complex "fixed action pattern." The sequence of motor activity continued long after the stimulus had ceased. The implication of this for theorizing about speech movements relates to the difficulty that has been experienced in accounting for the overlap in function, the transmission rates of neuronal fibers to provide continuous action, and the number of neuronal cells required to provide stimulus for the numerous simultaneous motor events that occur during speech. If such a trigger action as the one alluded to here exists in humans, it may account for the numerous fixed action patterns associated with speech production in a relatively simple manner.

FEEDBACK MECHANISMS

The role of auditory feedback in the monitoring of speech production has been so dramatically with us in the face of speech production problems of deaf children that it has taken a long time to focus attention on other feedback mechanisms. The papers on sensation in this *Report* discuss proprioception as a prime modality in learning of motor patterns. The impact of the research and study of this area is reflected in a recent textbook on language disorders (Berry, 1969) in which the author states that the importance of proprioceptive feedback extends much beyond articulatory movements to postural set, gesture, respiration, and phonatory action patterns. She draws the rationale for the importance of proprioceptive feedback from the following tenets:

> (1) Since motor patterns are the earliest events in the comprehension of speech, proprioceptive feedback must mediate between the acoustic stimulus and its perception.
> (2) Proprioceptive feedback signals from articulatory movements apparently are truly motor command patterns, i.e., they are temporal, spatial, neuronal patterns that activate entire muscle groups responsible for articulation of syllables, words, or phrases.

SPEECH SYNTHESIS

Motor aspects thought to be involved in perception are only part of the role of muscle function in speech. In addition to the efforts at the MIT Research Laboratory of Electronics to produce speech by synthesis according to distinctive phonological features of the language, other efforts to produce synthetic speech according to articulatory rules are under way in Bell Telephone Laboratories. Their efforts have led to the conclusion that more intersymbol influence exists in some parameters than in others. According to Coker (1968),[1] more information exists with respect to the horizontal coordinate of the central tongue than for the vertical height. There is a great deal of information about the degree of lip protrusion but there is relatively little information about lip closure and tongue tip raising. Since the Bell Laboratories' articulatory analogue utilized interpolation between target values affecting the tract configuration, the concepts of coarticulation and vowel reduction are a part of the system. As a result of this work, much information should become available about the movements essential to the production of phonemes and the interaction between movements. Some of this should be directly applicable to the modification of motor patterns used by individuals with speech disorders.

FUTURE RESEARCH

The concept of compensatory movements used in the production of speech sounds appears to be much in need of investigation. Jensen (1968) has provided some descriptive information regarding tongue tip placement for production of /s/ and /z/ by subjects with malocclusion. He studied only subjects who produced acoustically acceptable sounds so that no information was provided regarding the placement used by those individuals with malocclusion and defective sound production. If horizontal placement of the articulators, especially the tongue, is the more important parameter, then height of the palatal vault should not affect sound production to any major extent. That is precisely what we observe in patients who have had modification of the height of the palatal vault by the placement of acrylic appliances. The subject may demonstrate no change at all in speech production, and if sound distortions are present, they disappear rapidly.

Dentists have a good deal more training in biochemistry than is typical for speech pathologists. Almost no research has been conducted with regard to influences of various biochemical deficiencies on speech motor patterns. The presence of certain biochemical elements reflects the oxygen consumption by individual muscle units and thus reflects the amount of work or energy expended by the muscle tissue. Electronmicroscopic investigations of muscle tissue of the speech mechanism are almost completely lacking. One investigation (Kawano, 1968) reports a larger number of mitochondria present in the vocalis

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[1] Coker, C. H., personal communication (1968).

muscle than in any other laryngeal muscle. The significance of such a finding relates to the implication that there is a greater supply of energy to this muscle. The factor that makes this rather interesting is Kawano's finding that in dog larynges the cricoarytenoid muscle has the larger number of mitochondria.

In the area of speech synthesis, instructional simulation systems are being used to great advantage. However, to date, little application of the information from speech synthesis has been directed toward instructional systems for students of speech pathology or for individuals with speech disorders. It should be possible to design equipment that would monitor direction of tongue movements and provide feedback information in multiple modalities during sound production. Similar devices for providing multiple modality feedback with regard to oral pressure should be attempted and should prove useful in modification of speech disorders, particularly those in which the "voicing" parameter is disturbed.

Recently, we have become interested in the learning patterns of children who have more than one or two sounds in error. Tabulations of the number of production attempts used before the result is acoustically acceptable to the speech clinician has demonstrated that about four weeks are required, with approximately 10 to 20 trials per day being monitored, to achieve sound production in isolation. We have tabulated the results, considering variables of spontaneous production, auditory pattern provided, and phonetic placement provided. At the end of five or six weeks, the motor patterns required for accurate production of former errors appear stable. Instrumentation that would tell the individual who is learning sound modifications the degree to which movements are missing the target area would be most helpful.

Computer analogue studies are still in their infancy in spite of the fact that we have been attempting to develop them for years. Currently they do allow a calculation of orifice size at the velopharyngeal port and at the lips. We hope we are about to demonstrate that tongue height to the palatal vault can be calculated in essentially the same manner.

Application of computers for analysis, averaging, and print-out of data is so commonplace that it hardly needs to be mentioned. Computer use in clinical processes of diagnosis and programming of therapy is less well developed. Such applications to clinical aspects of dentistry are not known.

CONCLUDING COMMENTS

Too little information is available regarding the developmental aspects of speech motor patterns, although it is recognized that maturational components are important. Research efforts directed toward study of infant behavior have shown beyond any doubt that the newborn is a much more responsive being than was assumed earlier. The data also support the conclusion that infants at very early ages demonstrate self direction, and initiation of actions or self regulation. They are not subjects responding to stimuli alone but are capable of stimulating themselves.

In this paper I have suggested that we intensify our efforts to determine the way in which the movements of the various muscle groups of the speech mechanism act on the egressing breath stream. More complete analysis of the states of the breath stream with regard to such parameters as rate of flow, resistance to flow, pressure, and volume should enable us to predict the motor patterns that might be more essential in acting upon the breath stream in specific ways. Secondly, I have suggested that the role of motor function in speech production is equally involved in the perception of speech, the serial ordering of speech, and the feedback mechanisms monitoring speech. All of these functions must be studied in their developmental context as well as in their adult patterns.

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PROCESSES AND MATURATION OF MASTICATION AND DEGLUTITION

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The evolution of science is dependent upon the accumulation of a body of information and the coalescence of this information into organized patterns which stratify and clarify interrelationships. Formal theories are a natural extension of this process since they involve sifting the facts and structuring our orientation toward the information.

Such an approach has been neglected in large part with respect to mastication and deglutition. The task of attempting to unify the mass of conflicting and divergent information that continues to pour out of predominantly clinical studies of these functions is approached, therefore, with considerable trepidation. The results of such an endeavor may be expected to leave many questions unanswered.

To examine the processes and maturational patterns of mastication and deglutition, a logical approach might be to describe them in the newborn and then portray the structural and functional modifications through which they evolve until mature function is achieved. Our current state of knowledge concerning such evolutionary patterns allows us to present only a preliminary, rather meager sketch of the two limits—infantile behavior and mature function—and then to attempt to fit some of the known facts in between these limits. An attempt is also made in this paper to suggest some possible theoretic frameworks within which these data may be scrutinized, toward the final goal of achieving an accurate understanding of these complex processes.

MASTICATION

The complex neuromuscular activities of mastication involve mechanical, chemical, and enzymatic processes which include use of the lips, teeth, cheeks, tongue, palate, and all other oral structures to prepare the food for swallowing (Kawamura, 1964, Pritchard, 1965). Murphy (1965) has described the masticatory stroke in six phases:

1. The preparatory phase, in which the food is ingested and positioned by the tongue within the oral cavity, and the mandible is moved toward the chewing side. Murphy observed a slight, constant deviation to the nonfood side

an instant before the masticatory stroke began and used this point to identify the "precise beginning" of the preparatory phase.

2. Food contact, characterized by a momentary hesitation in movement. This he interpreted to be a pause triggered by sensory receptors concerning the apparent viscosity of the food and probable transarticular pressures incident to chewing.
3. The crushing phase, which starts with high velocity then slows as the food is crushed and "packed." Gibbs (1969) observed that when the central incisor is approximately 0.24 in. from closure, the jaw motion is stabilized at the condyle on the working side and the final closing stroke thereafter is guided by this "braced condyle." Ahlgren (1961) reported that the first three or four strokes in mastication typically emphasize the crushing phase and that they usually display equal and synchronous activity on both sides.
4. Tooth contact, accompanied by a slight change in direction but no delay. According to Murphy all reflex adjustments of the musculature for tooth contact are completed in the crushing phase before actual contact is made. This observation is supported by Møller (1966), who demonstrated decreases in electromyographically recorded activity of the mandibular elevator muscles before molar contact. Conversely, Beaudreau, Daugherty, and Marland (1969) reported a "distinct and discrete motor pause" consistently elicited in the temporalis and masseter following tooth contact.
5. The grinding phase, which coincides with transgression of the mandibular molars across their maxillary counterparts and is therefore highly constant from cycle to cycle. Messerman (1963) termed this phase the *terminal functional orbit*. Ahlgren (1961) noted that during this phase the bilateral muscular discharge becomes unequal and asynchronous, indicating that the person is chewing unilaterally.
6. Centric occlusion, when movement of the teeth comes to a definite and distinct stop at a single terminal point, from which the preparatory phase of the next stroke begins. Gibbs (1969) found that the jaw of subjects with normal occlusion remained in this position for "a considerable time" whereas the pause was rather brief for those with malocclusion.

Dahlberg (1961) observed that each individual seems to have a fixed pattern as to the number of times he chews a mouthful before swallowing it. Shiere and Manly (1952) termed the number of chews before swallowing a constant volume of food the *swallowing threshold*. According to Kawamura (1964), the typical chewing rate is one or two strokes per second.

The relationships between mastication and speaking are not well understood. Froeschels (1958) claimed that the movements involved in chewing and speaking are essentially identical, and on this as yet unproven assumption has developed a therapeutic approach using chewing movements to modify vocal patterns.[1] A recent study by Kawumura and Kamada (1967) raises doubts as

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[1] Weiss and Beebe (1952) have promulgated "the chewing approach" as a therapeutic tool for virtually all speech disorders.

to Froeschels' basic assumption of identity. They found reciprocal inhibition between cortically induced chewing-like movements and vocalization and also noted that the linguomandibular movement patterns were "completely different" during performances of the two functions. On the basis of this observation Kawamura (1968) speculated that chewing-vocalization reciprocity arises from a central switching mechanism. Disturbance of this switching would be expected to impair both functions.

DEGLUTITION

The physiology of deglutition has a long history of scientific and clinical interest. Information concerning this process has increased recently both in scope and precision through the use of such instrumentation as cinefluorography and electromyography. From the information currently available, four theories may be identified which have been used to describe this behavior (Wildman, Fletcher, and Cox, 1964). These are termed the *theory of constant propulsion*, the *theory of oral expulsion*, the *theory of negative pressure*, and the *theory of integral function*.

The theory of constant propulsion was developed by early investigators from anatomical and animal experimental studies. Magendie's classic statement of this theory which defined deglutition in oral, pharyngeal, and esophageal stages was published in 1816 (p. 58). He and other writers of his day assumed that the bolus was forced through these three stages by relatively independent, consecutive muscle propulsion forces.

The theory of oral expulsion evolved from the work of Kronecker and Melzer (1883), assisted by Falk. They devised a series of rather ingenious experiments on themselves and on dogs to establish time relationships during various parts of the swallowing act. They observed that the time lapse from the onset of swallowing until the bolus reached the cardiac sphincter of the esophagus approximated only 0.1 sec. From this and other data obtained they concluded that the bolus must be ejected directly from the oral cavity to the sphincter into the stomach by a piston-like action of the tongue and mylohyoid muscles. Cinefluorographic observations do not support this theory.

The theory of negative pressure was proposed by Barclay in 1930 from fluoroscopic observations of the swallowing act. He observed a "moment of radiolucency" in the pharynx when all existing orifices appeared to be closed. He also noted that the laryngopharynx and esophagus were elevated and dilated so that the bolus could be "popped in" as it exited from the oral cavity and upper pharynx. From these phenomena he concluded that a forward motion of the tongue and a dropping of the larynx creates a negative pressure at the initiation of swallowing which literally sucks the food as far down as the middle of the esophagus before further muscular action is needed for its propulsion. This theory was thoroughly discussed and essentially refuted by Saunders, Davis, and Miller in 1951. In 1956 Atkinson et al. provided rather conclusive evidence that Barclay's interpretation was erroneous. They used small transducers to sense pressure gradients in the pharynx during swallowing and found double-peaked, positive air pressure fluctuations.

Wildman, Fletcher, and Cox recently (1964) suggested the theory of integral function to emphasize the highly integrated, synergistic coordination of the total dynamic processes of swallowing. The concepts of this theory will be presented somewhat more completely.

For purposes of discussion, the processes of swallowing will be considered in four phases, the last three of which parallel the stages of swallowing proposed by Magendie (1816). The theory, however, stresses the fundamental unity of the act, and this concept should be kept well in mind as the discussion progresses.

Preparatory Swallow

The preparatory phase of swallowing begins immediately after liquids are taken into the mouth or as soon as solid foods are suitably masticated. It is signalled by collection of the food and formation of a more or less compact bolus which is moved to a characteristic swallow-preparatory position on the dorsal surface of the tongue. In the infant a second site of bolus accumulation is the valleculae between the base of the tongue and the epiglottis (Bosma and Fletcher, 1962). Movement of the bolus into the swallow-preparatory position is preceded by the establishment of a complete peripheral seal around the bolus by the lips and teeth or tongue anteriorly; the tongue and palate posteriorly; the palate superiorly; and the tongue, buccal teeth, and adjacent mucosae laterally. Positioning of liquids on the dorsum of the tongue before transporting the bolus to the swallow-preparatory position may be facilitated by suction created by moving the tongue posteriorly within the sealed oral cavity.

The average volume of water consumed per swallow by adults and by children was measured by Jones and Work (1961). They reported an average of 21.3 cc per swallow by men, 13.6 cc per swallow by women, and 4.6 cc per swallow by 1¼ to 3½ year-old children. They observed a relatively constant 0.27 cc per kilogram ratio between the volume of the swallow and body weight.

The mature swallow is apparently characterized by stabilization of the mandible. Proffit et al. (1964) called attention to pressure "of considerable magnitude" exerted in the molar region as the tongue tip is elevated to position the bolus.

Oral Phase of Swallowing

The oral phase of swallowing is initiated slightly before the preparatory positioning of the bolus is completely achieved. It is introduced by elevation of the palate from its tensor veli palatini depressed position against the pharyngeal surface of the tongue (Fletcher, 1958) and by a posterior movement of the tongue root and simultaneous vertical elevation of the hyoid bone and larynx (Shelton et al., 1960). Slight elevation of the hyoid during the previous swallow-preparatory positioning was also noted by Ardran and Kemp (1954). Fine coordination between respiration and deglutition is evidenced by a short respiratory pause which begins in this phase of swallowing and extends to the esophageal phase (Kawasaki and Ogura, 1968).

As soon as the posterior seal is broken, the bolus is moved posteriorly by a progressive anterior-to-posterior rippling contact of the tongue dorsum against the hard palate. Ardran and Kemp (1954) likened this movement to squeezing toothpaste from a tube. This analogy is more accurate for solid foods than for liquids, since the force of gravity causes the bulk of a liquid to flow ahead of the tongue constriction except at the upper and lower esophageal sphincters where the liquid is momentarily pooled. Ramsey et al. (1955) termed the progressive tongue-palate contact and the later tongue-pharynx contact a "stripping wave," thereby emphasizing its function as a final clearance activity rather than as a primary driving force.

When a large bolus is to be swallowed, most or all of it is moved into the swallow-preparatory position, then neatly sectioned by the tongue in consecutive swallows until the oral cavity is emptied of its contents (Ardran and Kemp, 1955).

Kydd and Toda (1962) and Proffit et al. (1964) found that during the oral phase of swallowing lingual pressures were almost identical around the anterior and lateral edges of the perimeter of the oral cavity. Kydd and Toda noted that pressure in the center of the palatal vault only reached about 60% of that at the peripheries. Elsewhere in this *Report,* Proffit and Norton (1970) report that pressures exerted at the lateral margins of tongue-palate contact are somewhat higher than those at the anterior margin. Nevertheless, the observations from each of these studies of oral pressure are consistent with the concept of the establishment and maintenance of an anterior and lateral seal during swallowing.

External postural stability during the oral phase of the mature swallow is provided by active contraction of the muscles of mastication (Kawamura, 1961; Sheppard et al., 1959).

Pharyngeal Phase of Swallowing

The pharyngeal phase of deglutition is begun as the bolus is released from the tongue and thereafter passes through the fauces. Active participation of the pharynx is elicited by palate and bolus contact with the pharyngeal wall (Fletcher, 1958; Sumi, 1964). This action consists of an elevation of the entire pharyngeal tube and a sphincteric reduction in the lumen between the upper pharyngeal wall and the soft palate (Bosma, 1957). A ridge of Passavant may or may not be present to augment this valvular closure (Fletcher, 1957).

Closure of the palatopharyngeal portal and entrance of the bolus into the pharynx is followed shortly by a synergistic, peristaltic-like tongue-pharynx stripping wave that progressively propels the remnants of the bolus from the pharynx. Whether the tongue or the pharyngeal wall is the major contributor to the propelling force developed is irrelevant since the action of both structures is plainly complementary (Ramsey et al., 1955).

Passage of the bolus through the pharynx during mature swallowing is signalled by an anterior movement of the hyoid bone (Shelton, Bosma, and Sheets, 1960). Shelton, Bosma, and Sheets also described an alternative pattern in the swallow pattern of some people, an oblique upward and forward movement of the hyoid. This variation apparently reflects different ways in which the bolus is being handled. Ramsey et al. (1955) reported that when a large bolus is swallowed, the hyoid bone moves in the oblique upward and forward pattern; whereas when the same subject swallows a small bolus, the hyoid motion pattern is first upward, then forward. Cinefluorographic observation of infantile swallowing displays yet a third pattern, which has the strong forward movement as the first vector and a vertical rise later in the act.

Bosma (1957) described an abrupt final elevation of the larynx as the bolus reaches the hypopharynx. This rise is followed by elevation of the floor of the hypopharynx and opening of the esophageal sphincter (Negus, 1948).

Esophageal Phase of Swallowing

The esophageal phase of swallowing is introduced by passage of the bolus through the cricopharyngeal sphincter. True peristaltic movements then move the bolus through the upper part of the passageway. The peristaltic wave may be replaced as the propulsive force in the distal parts of the channel by simultaneous contraction along lower segments (Vantrappen and Hellemans, 1967). During the esophageal phase of deglutition the tongue, palate, and hyoid bone return to their preswallow positions.

The total processes of mastication and deglutition, then, encompass a highly coordinated and complex system in which all phases are integrated together with few points of clear demarcation.

THE TONGUE-THRUST PATTERN OF ORAL ACTIVITY

In recent years considerable attention has been focused on a pattern of oral activity which includes the following attributes: minimal contraction of the muscles of mastication during swallowing (Rix, 1946, 1948; Tulley, 1953), strong contraction of the perioral musculature (Rix, 1946, 1948; Tulley, 1953), a thrusting movement of the tongue against or between the incisal dentition (Neff and Kydd, 1966), movement of the hyoid bone in the oblique or infantile pattern (Shelton, Haskins, and Bosma, 1959), and distortion of the linguapalatal speech sounds, especially the sibilants (Fletcher, Casteel, and Bradley, 1961). The criterion characteristic of this pattern is the anterior directional orientation of lingual movements, hence its label of *tongue thrust.* Other terms, such as *perverted swallow, oral-facial muscle imbalance, infantile swallow,* and *reversed swallow,* have been suggested from time to time but have not gained general usage, because they reflect specific and restrictive interpretations concerning the presence or etiology of the pattern as a pathological condition.

No single characteristic of the tongue-thrust pattern of oral activity is constant. Neff and Kydd (1966) have shown that the teeth may be brought into occlusion by persons who are legitimately classified as tongue thrusters. Leech (1958) and Subtelny (1965) questioned the validity of unusual contraction of the perioral musculature as a sign of tongue-thrust swallowing. Fletcher, Casteel, and Bradley (1961) and Subtelny, Mestre, and Subtelny (1964) have shown that many children who may demonstrate a tongue-thrust pattern of swallowing do not have associated speech errors. Writers such as Rix (1946) and Straub (1951) stress the deleterious effects of this "abnormal" swallowing pattern on dental occlusion; however Cleal (1965) has observed that a thrust of the tongue tip between the incisors and lack of contact between the molars can be shown in subjects with normal dental occlusion. This variability led Scott (1961) to conclude that insofar as dental occlusion was concerned the pattern of oral activity is somewhat irrelevant since a basic cause-and-effect relationship between intraoral and perioral muscular forces and arch form has not been established. This last position recently was attacked strongly by Jacobs (1969), who observed that when the sum of dynamic movement forces, static isometric forces, and passive tonic forces are not balanced by equal opposing forces "even minor muscular forces of such low values as 1.68 g . . . [are] . . . capable of moving teeth."

Cleal (1965) suggested that use of a "normal" vs "abnormal" dichotomy to describe various patterns of oral activity has hindered the development of an accurate concept of the relationships between soft tissue behavior and skelatodental configuration and the adaptive capabilities of the stomognathic system.

In spite of the inconsistencies noted, most clinical and experimental evidence continues to suggest that the tongue-thrust pattern of oral activity is likely a meaningful cluster of behavioral signs and, as such, is worthy of continued scrutiny to determine more precisely its specific characteristics and possible place in the heirarchy of oral physiology.

Etiology of Tongue Thrusting

Another point of considerable controversy with respect to occurrence of the tongue-thrust pattern of oral activity focuses upon its etiology. Speculation in this regard may be summarized under the following six alphabetically arranged headings. The references indicated in this section are not meant to indicate that the particular person cited believed only in that particular explanation, nor that the ones cited are the only proponents of that particular viewpoint. Rather, they are included to document the fact that someone has indicated in a formal publication the etiological explanation described.

1. Genetic
    a. Inherited variations in oral-facial morphology which precipitate a tongue-thrust motion pattern (Ballard and Bond, 1960; Gwynne-Evans, 1956).

   b. Inherited orbicularis oris hypertony resulting from specific anatomical configuration and neuromuscular interplay and generating a tongue-thrust pattern of motion (Cauhépé, 1955).
   c. Genetically predetermined pattern of mouth behavior (Ballard, 1959).

2. Learned Behavior (Habit)
   a. Improper bottle feeding which results in "abnormal" functional patterns of lingual movement in the form of tongue thrust (Straub, 1951).
   b. Protracted period of tenderness or soreness of gum tissue and teeth that keeps the teeth apart during swallowing and thereby changes the swallowing pattern (Truesdell and Truesdell, 1937-8).
   c. Prolonged thumb sucking with the habitual movements generalized to tongue activity (Teuscher, 1940).
   d. Tongue held in open spaces during mixed dentition and extension and habituation of such postures into other mobile activities of the tongue (Rogers, 1927).
   e. Prolonged tonsillar and other upper respiratory infections which cause adaptive patterns in tongue movements and which movements are retained after the infection subsides (Moyer, 1958, pp. 118-119).

3. Maturation
   a. Tongue thrust present as part of normal childhood oral behavioral pattern which is gradually modified as the lingual space and suspensory system change (Fletcher, Casteel, and Bradley, 1961; Wildman, Fletcher, and Cox, 1964).
   b. Tongue-thrust pattern as evidence of late maturation from infantile suckle-swallow (Rix, 1953).
   c. Late maturation from or retention of immature patterns of general oral behavior of which tongue thrust is a symptom (Tulley, 1956).

4. Mechanical Restriction
   a. Constricted dental arches which cause the tongue to function in a higher-than usual position (Gwynne-Evans, 1956).
   b. Macroglossia which limits space in the oral cavity and forces a forward thrust to manipulate the bolus (Breitner, 1942).
   c. Enlargement of the tonsils and adenoids which reduces the space available for lingual movements (Moyer, 1958, p. 227; Strang and Thompson, 1958, p. 206).

5. Neurological Disturbances
   a. Hyposensitive palate which precipitates crude patterns of food manipulation and swallowing (Ray and Santos, 1954).
   b. Disruption in the tactile sensory control and coordination of swallowing because of inadequate underlying skeletodental configuration (Cleal, 1965).

c. Gross neuromuscular deficiency which includes a tongue-thrusting movement as part of a general extensor thrust pattern (Ingram, cited by Hopkin and McEwen, 1957; Palmer, 1948).
d. Moderate motor disability and loss of precision in oral function (Bloomer, 1963; Shelton, Haskins, and Bosma, 1959; Strang and Thompson, 1958, pp. 74-76).

6. Psychogenic
   a. Substitution of tongue thrust for forcibly discontinued finger sucking (Teuscher, 1940).
   b. Exaggerated motor image of tongue (Froeschels and Jellinek, 1941).

A BIOGENETIC MODEL OF ORAL ACTIVITY

An attempt will be made now to organize the data and observations concerning oral structure and function into a general model. Although the discussion to this point has made relatively little mention of sensory feedback in the process of physiologic development, Bobath (1967), Smith (1961), and Rood (1954) all have stressed its importance in the integration of any emerging motor system. The theory of neuromotor integration proposed by Smith is especially cogent to the present considerations. This extention of cybernetic theory states that sensory feedback organized in space and time dynamically links and controls the receptor and motor systems of an organism. This control is accomplished at three levels: control of postural movements in relation to gravity, of transport movements in relation to bilateral differences in stimulation, and of manipulative movements in space. According to this formulation any disturbance in the neurogeometric organization of motion may be expected to result in new patterns of perceptual-motor function.

The oral cavity of the human infant is vastly different from that of an adult. The most striking characteristic of this difference lies in the comparative massiveness of the tongue and in the orientation of its suspensory system. Although the general dimensions of the human body change by a ratio of five to one, Hopkin (1967) showed that the mean dimensions of the adult tongue are only double those of the neonate. Thus, the human infant has a relatively massive tongue housed in a comparatively small oral cavity.

The suspensory system of the infant tongue also differs markedly from that of a mature person. The orientation of the corpus of the tongue to its suspensory system gradually expands during the prenatal period of development from an anteroposterior source of motive power to a multidirectional force capability. This trend toward expansion of the peripheral attachment continues well into postnatal development (Fletcher, in press).

The lingual system of the newborn infant is basically a dual reciprocating structure with the mandible as the anterior hub and the hyoidstyloid complex as the posterior hub. Thus the system is highly stabilized in space and structurally capable of functioning in the whole-organ activities of the infant suckle-swallow, in the following manner (Ardran, Kemp, and Lind, 1958; Bosma, 1963; Gwynne-Evans, 1951).

When the nipple is placed in the infant's mouth, he immediately generates a complete peripheral seal around it by apposing the tongue and lower lip against its inferior and lateral surface and by drawing the soft palate firmly against the tongue root. The lateral seal is supported by the fat pad embedded in the cheeks of the infant and the posterior seal is facilitated by the leverage obtained as the tensor veli palatini muscles pass around the hamular processes which are oriented much lower with respect to the tongue of the infant than of the adult. This seal allows the infant to generate the suction through which he can stabilize the nipple within the oral cavity. The tongue, lip, and mandible are then raised in concert and simultaneously the tongue tip is thrust forward against the base of the nipple. The compression which results from these movements is further supported by a rippling motion along the tongue dorsum, beginning slightly behind the tip. This total action expresses the milk and carries it to a swallow-preparatory position between the palate and the tongue.

The primary neurogeometric mechanisms to handle the suckle-swallow are differentiated during fetal development (Pritchard, 1965) although they are not developed fully until after birth (Crump, Gore, and Horton, 1958). Gryboski (1969) observed that swallows of premature infants are preceded by three or four suckling bursts and occur during pauses between the suckling bursts; whereas swallows of the more mature infant are frequently present during suckling bursts which contain as many as 30 consecutive suckle movements without pause.

Postnatal ingestion of solid foods involves differentiation of postural and transport motions which will allow more bulky foods to be handled. Consistent with neurogeometric theory the initial attempts by the infant to ingest solid foods are in the form of suckle movements. These movements are characterized by elevation of the mandible and forward thrust of the tongue in contact with the lower lip. The nonliquid foods, however, provide a new set of sensory inputs which, according to theory, would be expected to set into play a motor reorganization and a new set of outputs. The reactive feedback from the new bodily movements would tend, in turn, to bring the new response system into stabilized congruence. This new cybernetically generated and regulated reorganization would be posited as the activation of a genetically preprogrammed sequence which lies dormant until the appropriate set of sensory experiences precipitates its arousal.[2]

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[2] An additional important point should be mentioned. This is that the development of a delicately coordinated pattern of action presupposes the maturation of all tissues and processes involved to the level at which the action demands will be imposed upon them. As Meader and Muyskens (1962, p. 53) point out, the tissues and processes do not mature simultaneously but, rather, they mature in accordance with a certain "time-place framework." Thus, the tongue may have achieved certain gross developmental characteristics but still be incapable of many finer movements because it lacks the internal structural refinement to perform them.

Cinefluorographic observation of infant ingestion of solid foods indicates that postural stability is achieved by elevating the mandible and thrusting the tongue firmly forward to elevate the bolus crudely to the dorsum of the tongue and transport it into the swallow-preparatory position. In this action mandibular posturing seems to continue to serve primarily as a supporting buttress to aid in gross positioning of the tongue. Perioral contraction provides additional stability in the anterior oral region. Bosma (1963) called attention to the importance of the labial enclosure of the oral cavity as a developmental landmark in oral function.

As the oral cavity expands through growth, the intrinsic lingual musculature matures and becomes capable of more refined movements, and the teeth erupt to serve as a new potential source of sensory input, new sets of reactive responses may be anticipated. In 1886, Wassilief described two patterns of lingual reflex which suggest that such reorganization does indeed occur. He found that mucosal stimulation by touching or rubbing the surface of the infant tongue elicited suckling movements in the infant. Repeatedly touching or rubbing the adult tongue caused it to curve into the shape of a spoon. This latter posture is that seen as the bolus is collected in the mature preparatory swallow.

The addition of dental occlusion provides an important new source of stabilization for swallowing. Sensory feedback from the teeth in occlusion during swallowing could signal the presence of a new avenue to achieve a stable postural balance of the oral cavity and thereby release the tongue for more precise control of the bolus during deglutition. From myometric data Proffit, Chastain, and Norton (1969) suggested just such a developmental pattern. They noted two patterns of swallow which they felt were intermediate between the traditionally described infantile and adult patterns. These patterns consisted of a tongue thrust with the teeth apart and a tongue thrust with the teeth together. They felt the adult pattern would emerge from the latter movements.

Within the foregoing framework the tongue thrust pattern of oral activity could represent either a form of developmental arrest or a regression to a less mature phase of physiologic function. Thus, if a particular child did not achieve the neurological competence demanded to segment the lip-tongue-mandible complex in response to the changing cues from an expanding oral cavity, he could remain in an extensor thrust-like swallow pattern. Alternatively, if neurologic maturation progressed adequately, but the geometric configuration of the mouth or the tongue did not change sufficiently to provide appropriately different sets of new sensory cues, the swallow pattern would remain at some less-than-mature level. A similar arrest in development could be conceived as the result of more transitory phenomena, such as prolonged infection and missing dentitition, which would disrupt sensory cues during critical developmental periods. Finally, certain types of trauma to the neurological system may be expected to precipitate regression to previous patterns of oral activity, including the tongue-thrust swallow, as the earlier sensory cues reestablish their prominence.

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THE TONGUE AND ORAL MORPHOLOGY: INFLUENCES OF TONGUE ACTIVITY DURING SPEECH AND SWALLOWING

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Tongue and lip activity definitely can affect the form of the oral cavity. In extreme cases of macroglossia or aglossia, the expansion or collapse of the dental arches is obvious, and the dental malocclusions associated with tongue "habits" also are well known. We do not know, however, how important tongue activity is in determining normal dental arch form, or its precise role in the etiology of malocclusion.

The functional matrix theory (Moss and Salentijn, 1969), which implicates functional activity of soft tissues as the stimulus for hard tissue growth, emphasizes the general importance of function for normal development.

Tongue activity occurs primarily during speaking and swallowing (including bolus manipulation prior to swallowing). This paper reviews recent studies of the oral phase of swallowing, with particular reference to form-function relationships in the oral cavity, and also discusses lingual pressure studies of speech.

DESCRIPTION OF NORMAL SWALLOWING, ORAL PHASE

The oral phase of swallowing has been described by direct observation, by cineradiographic studies, and to some extent by palatographic and lingual pressure studies. Swallowing is different in infants and adults. Bosma has recently reviewed his work on infant deglutition (Bosma, 1969). Farrieux and Milbled have also published radiographic illustrations of newborn deglutition (Farrieux and Milbled, 1967). The classic cineradiographic description of suckle-swallowing in the newborn involves a position with the head extended and the tongue low in the mouth, extending anteriorly under a teat or nipple to contact the lower lip. The jaws are relatively wide apart, and the lips are pursed around the nipple. As the liquid collects on the tongue, a wave of peristaltic-like activity carries it backward along the center of the tongue and propels it into the oral pharynx. The jaws remain apart and lip activity continues during the swallowing act. Since there are no teeth, the tongue is free to extend between the gum pads. Cineradiographic descriptions of swallowing in infants have not been extended by use of intraoral instrumentation because of the difficulty in obtaining such data.

With the eruption of teeth and the addition of solid food to the diet, the infantile swallow is gradually replaced by a more adult swallow pattern. The classic description of adult swallows involves tongue movements associated with mastication in preparation of a semiliquid bolus. The bolus is collected on the center of the tongue, and placed against the hard palate. As preparatory movements by the tongue end, the teeth are brought together, and the tip of the tongue contacts the palate posterior to the central incisors. The lips relax while a wave of contraction carries the bolus into the pharynx.

The classic, idealized descriptions of swallowing are probably correct for normal infants, but it is known that many apparently normal adults do not swallow in the fashion described as the typical adult swallow (Cleall, 1965). It is interesting to speculate that these individuals have progressed through some but not all the transitional stages between infantile and adult swallows. The existence of transitional types of swallows has been presumed but not documented. On the basis of cineradiographic findings by other investigators and our lingual pressure studies, we have proposed that the anterior open-bite malocclusion which trouble orthodontists is related to a transitional "teeth together, tongue against lower lip" swallow pattern (Proffit, Chastain, and Norton, 1969). Studies are now underway at the University of Kentucky to attempt to document changes in swallow patterns in children, following individuals longitudinally.

An effort should be made to describe the variety of types of swallow pattern which are intermediate between the infantile and adult swallow. If this can be done, it will allow a much more logical framework for clinical treatment of associated problems than has been the case in the past, when various unusual swallow patterns have been labeled as habits. For instance, a child age 9-11 often can be taught to swallow in the adult fashion very readily (Fletcher, Casteel, and Bradley, 1961; Jann, Ward, and Jann, 1964). An apparently similar individual in the late teens or early adult years has great difficulty in changing his method of swallowing. Such an observation could be explained on the basis of a normal transition sequence. As the time of normal transition is passed, it becomes increasingly difficult to go through the transitional sequences.

LINGUAL AND LABIAL PRESSURES DURING NORMAL SWALLOWING

Although papers continue to appear describing various types of apparatus which could be used for labial and lingual pressure recording, the technical problems involved in this type of recording were largely solved in the early 1960s. A body of relatively consistent data is now developing, with major contributors being Gould and Picton in England, Lear and coworkers at Forsyth Dental Center, and Proffit and coworkers at the National Institutes of Health and later in Kentucky. Labial pressures are easier to measure than lingual pressures because the problem of the subject's consciously or unconsciously avoiding the pressure transducer is less likely. Under the best of circumstances, data for lingual pressure must be regarded with some suspicion because of the possibility of such "physiologic reactance" (Fry, 1960). Even with this difficulty, pressure profiles around the dental arches, including the hard palate, are now available.

All studies to date have demonstrated considerable individual variation in labial and lingual pressures. A given individual tends to reproduce himself rather well in this respect, but subjects who are similar in dental and anatomic characteristics may exert quite different pressures with tongue or lips. The figures discussed in this section, extrapolated from our work (Proffit, Chastain, and Norton, 1969; Proffit et al., 1964) and that of others (Lear 1968; Lear and Moorrees, 1969; and Gould and Picton, 1964, 1968) are for a "typical normal individual." We have arbitrarily expressed the range of expected differences between subjects. This variation is larger than would be found within a single subject.

On this basis, tongue pressure against the maxillary incisors and anterior hard palate during normal swallowing is 75 ± 50 gm/cm^2. Pressure by the tongue tip is typically exerted for one second during a swallow, but the pressure rises to a peak and falls away, so that the area under the pressure curve or "time-pressure integral" is a better measure of the pressure-time relationship. Such figures would be 50 ± 25 gm-sec/cm^2 for each swallow. Pressures exerted by the sides of the tongue against the hard palate in the molar region are somewhat higher, 140 ± 50 gm/cm^2 and 100 ± 30 gm-sec/cm^2 being typical. In normal swallowing, a deep overbite may cause the tongue tip to contact the lingual of mandibular incisors, and resting pressure also may be encountered in this region. Lingual pressure against the mandibular molars during swallowing may or may not occur. The best figures are those of Winders (1962), who reports a mean of approximately 90 gm/cm^2 for tongue pressure against both mandibular incisors and molars.

Lip and cheek pressures during swallowing are lower than tongue pressures in all areas. Although lip pressures are more sustained and peaks of activity are not so sharp as with lingual pressure recordings, pressure waves are seen also in labial-buccal recordings during swallowing. Data for lip and cheek pressure are more complete than for lingual pressure, for the reasons already mentioned, and these vary considerably at different locations. Wide individual differences have been noted. Some individuals have measurable resting lip or cheek pressure (Proffit et al., 1964; Gould and Picton, 1968).

Labial pressures during swallowing are highest at the corners of the mouth, in the premolar region. For subjects with normal occlusion, they average 140 ± 40 gm/cm^2 in the maxilla, 115 ± 35 gm/cm^2 in the mandible. Pressures in the molar region are lower, particularly in the maxilla: 80 ± 25 gm/cm^2 in the mandible, 30 ± 15 gm/cm^2 in the maxilla. Lip pressure against the central incisors is about the same in both arches, approximately 55 ± 20 gm/cm^2. Lip pressures tend to be somewhat higher in the anterior and premolar regions in individuals with Class II/1 malocclusion (protrusion of maxillary teeth). Otherwise, no differences have been found in subjects with malocclusion (Gould and Picton, 1968).

Integral (time-pressure) data for labial-buccal locations have been used by several investigators but have not been tabulated so well as Gould and Picton's data. The picture which emerges from integral data is similar: labial pressure is lower than lingual, even when its longer duration is taken into account. When time is considered, pressure at the corner of the mouth may be more similar to lip pressure elsewhere. The data are not convicing on this point.

The time relationships of lingual pressure application in given areas during swallowing are interesting, since this method allows a three-dimensional view of rapid tongue movements. Our lingual pressure studies show that tongue movements during swallowing in most individuals first involve positioning of the tongue posteriorly, as shown by an initial contact with pressure transducers in the molar region. A sharp spike of pressure against the anterior region indicates placement of the tongue tip as the swallowing wave begins, and a spike of pressure posteriorly 0.1 sec later indicates passage of the pressure wave in the molar region. With multiple pressure transducers, it is possible to observe details of tongue activity which cannot be detected in other ways.

The reproducibility of the foregoing figures has been a difficult problem, particularly with regard to lingual pressure variations. A given individual tends to reproduce himself more closely than the broad and arbitrary ranges given. For instance, a certain individual will tend to produce light pressure against the maxillary left first molar area, averaging 90 $\mathrm{gm/cm^2}$. On a given day, 10 successive swallows might all fall between 75 and 105 $\mathrm{gm/cm^2}$. If the same individual is recorded three days later, however, using the same equipment and with adequate precautions to prevent artifacts, pressures may average 100 $\mathrm{gm/cm^2}$, with a range of 85 to 115 $\mathrm{gm/cm^2}$. Nevertheless, this individual would remain in the group of persons who produces relatively light lateral tongue pressure.

There are no published data indicating that repeated labial pressure recordings on the same individual at daily or weekly intervals specifically show reproducibility, but a similar phenomenon probably occurs in regard to labial pressure. We speculate that the variation may relate to the psychologic state of the individual, both with regard to his general "nervous tension" and his adaptation to the presence to the recording equipment.

There have been no studies of labial or lingual pressures in individuals with markedly abnormal oral morphology, and relatively few data exist regarding labial or lingual pressures in individuals with dental malocclusion. Investigators who have looked for correlation between labial pressures and malocclusion have not been able to document such a relationship, except that cheek pressures may be somewhat higher in individuals with malocclusion. Kydd and his collaborators (1963) reported higher-than-normal tongue pressures against the anterior teeth in "tongue thrusting" individuals who relapsed into open bite. This seems a perfectly reasonable finding, which would explain how the open-bite malocclusion returns after having been corrected orthodontically. Other investigators have not confirmed this finding, however. Our work has shown that children who have a clinical tongue thrust may have either high or low anterior pressure.

Part of the difficulty is related to the classification of dental malocclusion which is used. The Angle classification is based on simple dental characteristics related to the sagittal plane of space. The types of malocclusion related to tongue function, on the other hand, are primarily vertical problems, which are not considered in this classification. It may be that better classification systems would help point out relationships between labial or lingual pressures and malocclusion types. As we will show, the relationships are probably not as simple as once was hoped.

LINGUAL AND LABIAL PRESSURES DURING SPEECH

The instrumentation developed for studies of labial and lingual pressures during swallowing is also applicable to studies of speech. As with swallowing, distortions due to presence of the instruments must be considered in interpreting data from the study of normal speech. In speech studies, however, judgments of listeners to the acoustic signal provide an indication of the distortions (if any) produced by the measuring device. Subjects usually adjust to speaking with a pressure-sensing appliance in their mouth in a few hours, so that trained listeners report no more distortions or articulation errors than the subject made without an intraoral device (McGlone and Proffit, 1967). This does not mean that the speech articulation is necessarily "normal," but that the speaker has accommodated to the appliance and can produce the required utterance. We have found that once this accommodation has been achieved, the articulation remains consistent for repeated utterances. Inconsistent results were reported in Malecot's study (1966), but his instruments were such that they would have required greater accommodation.

Tongue and lip pressures against the teeth and alveolar processes are associated with certain sounds, both vowels and consonants. Lingual pressure against the anterior maxillary alveolar ridge associated with linguo-alveolar consonants is obvious, as is labial pressure against incisors associated with bilabial consonants. Lingual pressure against maxillary molars is associated with most vowel sounds. All these pressures are considerably lighter than the pressures associated with swallowing, but during a day's time speech may (on a time-pressure basis) contribute as much as swallowing to the total pressure on the teeth (Fletcher, Casteel, and Bradley, 1961). With regard to lingual pressure, articulation of [t] may produce 25 ± 10 gm/cm^2 or 20 ± 8 gm-sec/cm^2 in the maxillary molar region and 30 ± 10 gm/cm^2 and 15 ± 5 gm-sec/cm^2 in the maxillary incisor region. Lateral pressure in the molar region usually is higher on the left. Other consonant sounds produce pressures of similar magnitude. Lateral pressures in the molar region during vowel sounds are also of similar magnitude (McGlone, Proffit, and Christiansen, 1967).

At one time, it seemed that it might be possible to differentiate linguo-alveolar consonant sounds on the basis of the pressures and pressure patterns during their articulation. This has proved not to be the case. The wide variation in group data for the same consonant, and the consistency within individual speakers, indicate that pressure values reflect the individual subject's articulatory patterns more than syllable similarities of all speakers (McGlone and Proffit, 1967; Malecot, 1966; Proffit, Palmer, and Kydd, 1965).

Using pressure-time integral values, consistent differences in lingual pressures have been found relative to some speech parameters. Tongue pressure is neither as great nor as long-lasting for syllables containing consonants in their final syllabic position as for those with consonants in the medial and the initial positions. Rate of syllable utterance also may influence the pressure-time integral. McGlone, Proffit, and Christiansen (1967) found higher pressures and greater variability for syllables uttered rapidly than for syllables produced at a slow rate, but Brown (1969) reports the opposite. Lingual pressures also appear to be related to loudness and vocal effort of the utterance. Brown reports an increase in the mean pressure-time integral with increases in vocal intensity, and Leeper and Noll (1969) report the same results for vocal effort. There are as yet no data relating lingual pressure patterns to types of speech defects or articulation errors, although this information will be of interest to speech clinicians as it becomes available.

It seems reasonable to assume that as a person uses his speech skills over a period of time, he develops certain habit patterns which become more precise as he matures. Integrated time-lingual pressure should reflect this reduction in magnitude of contact and in variability.

Comparison of values from several studies shows that time-pressure integrals for adults during speech are, in fact, lower than similar measures for children. For example, Brown (1969) reports a mean of 2.77 gm-sec/cm^2 and a standard deviation of 0.97 gm-sec/cm^2 for anterior maxillary contacts for syllables containing [t] produced slowly by adult males. He found a mean value of 19.63 gm-sec/cm^2 with a standard deviation of 9.34 for children performing the same task. From these values McGlone and Proffit (1969) hypothesized that children lack the precise articulatory movements found in adults. Serial studies of lingual pressure as children grow and speech develops would improve our knowledge of speech acquisition.

There are many possible directions for fruitful future research in this area. Lingual pressure studies should be coordinated with data from other experimental methods, such as air pressure-flow and palatography. These studies should be expanded to include a broad normally developing group who can be used for standard comparisons. Pressure studies can yield useful information about tongue activity in aphasics, hemiplegics, and less severely speech-handicapped individuals. Lingual pressure also can be used to study the response of individuals to radical changes in their oral morphology, as for instance after orthodontic surgery.

RELATIONSHIP OF LINGUAL AND LABIAL PRESSURES TO DENTAL ARCH FORM

The size of the oral cavity, and particularly the dimensions of the dental arches, vary considerably in normal individuals. Within general limits, dental arch dimensions correlate with other bodily proportions, but the correlation is not great, and large dental arches in small faces or small, collapsed arches in large, broad faces are common. Studies of lingual and labial pressures during swallowing and speech have yielded minimal information regarding possible relationships of these pressures to arch forms. As we have already noted, there are poor correlations between lingual and labial pressures and types of malocclusions as classified by the Angle system. Even in open-bite malocclusion, direct pressure against the teeth during swallowing is far from the whole story.

In our longitudinal studies of children, we have found no relationship between the increment of lateral growth of the maxillary arch (increase in intermolar width) and lateral lingual pressure during swallowing (Proffit, Chastain, and Norton, 1969). The arch dimensions behave as if they were rather independent of pressures during swallowing activity. If the scope of the inquiry is broadened to include pressures during all activities, not just during swallowing, this picture changes only slightly. The best data are those of Lear and Moorrees (1969), who recorded seven subjects over a two-hour period, and used projected 24-hour totals to obtain pressures integrated over that period. He found mild pressure asymmetries in his subjects (higher pressure on the left than right), but these individuals had nicely symmetric arches. The one individual in the study who had asymmetric dental arches had relatively symmetric forces applied against them. The asymmetry differences which Lear recorded may have been due to recording artifacts (to which he ascribed them). We also consistently record asymmetric lingual pressure during swallowing, and it seems to us more likely that Lear's recordings of asymmetry were accurate. In any case, this evidence also indicates an insensitivity of dental arch form to pressures during activity.

Lear's work has altered the classical concept of the "balance of forces" between the opposing labial and lingual musculature. Since the teeth tend to remain in a stable position, they are by definition in an equilibrium situation. From the beginning of pressure recordings, it has been apparent that peak tongue pressure was higher than lip pressure. There remained the possibility that the longer duration of lip pressure would balance out the more intense but shorter periods of tongue pressure, allowing a true balance of pressures. Even with the projected 24-hour recordings, Lear found that lingual pressure considerably outweighted labial pressure in five of his seven subjects. Since no investigator ever has been able to detect anything approaching consistent balance of opposing muscle forces, this simplistic notion of the equilibrium theory of tooth position must be revised.

A final point of evidence can be derived from examination of children and adults whose oral form has been changed rapidly and dramatically. This occurs in children who undergo rapid palatal expansion (up to 8 mm expansion in 3-4 weeks) and adults who have surgical procedures to reposition jaws or alveolar segments. We are studying lingual and labial pressure in these patients. We have noted no consistent adaptation in tongue activity, though individuals do show large changes in pressure patterns during swallowing. This picture also is consistent with a wide range of acceptable tooth positions, little influenced by pressures during deglutition.

Perhaps reflecting an unconscious bias produced by the Angle classification, the studies mentioned refer only to horizontal tooth positions. Teeth, it appears, are not readily pushed back and forth buccolingually by tongue and lip pressures, though they will respond outside a range of tolerance. What about vertical movement?

Clinical orthodontists have observed that vertical dimension dysplasias and open-bite problems appear to be caused by differential eruption of incisors relative to molars (Schudy, 1968). The eruption of maxillary teeth seems particularly affected (Merow, 1962; Creekmore, 1967). How does the eruption of teeth, the concomitant of normal vertical growth, respond to tongue-lip forces? The malocclusion classically associated with tongue activity is the anterior open bite. We feel it is not produced by incisors being moved bodily to a new position. Instead it appears to develop as eruption of anterior teeth is impeded while posterior teeth erupt even further than usual. This is true in adults as well as children. An open bite in an adult can develop as a lower resting mandibular position appears and molars—but not incisors—erupt.

We do not know what forces are needed to affect vertical movement of teeth, nor what is required to deflect a tooth buccally or lingually as it erupts. Since teeth normally erupt until they contact something, the occurrence of stable anterior-open-bite malocclusions indicates that, in this case, intermittent tongue contacts can influence tooth position vertically. Exactly what kind and duration of pressure is not known.

With regard to dental arch form and tooth position, resting pressure of tongue and lips is an important variable which may have been interpreted incorrectly. Orthodontic clinical experience has demonstrated amply that teeth tolerate and withstand intense, short-acting forces while they respond to even very small forces acting over prolonged periods of time (Weinstein et al., 1963). Although most tongue and lip activity occurs during swallowing and speech, it may be that the buccolingual pressures during activity are less important than the light but prolonged pressures created by tongue and lips at rest. If this hypothesis is to be proved true, better methods of studying tongue position will be required, and emphasis in collection of pressure data will have to be changed from studies of tongue activities during motion and maximum pressures, to study of the pressures generated at rest. By their nature, resting pressures are subtle and hard to evaluate, particularly lingual resting pressures.

Brader (1969) recently has proposed an ingenious hypothesis relating resting pressures to arch form. He reasons, as have others in recent years (Tulley, 1969, for example), that resting pressures define a trough or equilibrium area within which teeth may be arranged. Most mathematical descriptions of the dental arches are based on the catenary curve (the form which a fine chain would assume when suspended at its ends). Brader uses instead a closed curve (an ellipsoidal variation with three centers of rotation rather than two), which seems to provide excellent fit of dental arch forms, especially in fitting the inward curve of the molars posteriorly. It also has the advantage of being defined by internal centers of rotation and radii.

If one considers the dental arch to be the anterior aspect of a closed curve, it is possible to examine existing buccal and lingual pressure data from the point of view of forces across an elastic membrane. The appropriate engineering principles (to which any elastic container, whether it be biological or otherwise, must conform), indicate an inverse relationship between force and curvature of the container. This means that the tighter the curve, the greater the pressure, or, pressure is greatest where curvature is tightest. Using radii derived from his curve, Brader obtains a fit of mean pressure data which is consistent with this relationship. D'Arcy Thompson (1942) has shown many examples of biologic structures which can be explained by just such applications of engineering principles, so it would not be surprising if this were true also for dental arch form.

Brader feels that, given adequate pressure measurements, his equations could be used to calculate optimum tooth positions. Although his assumptions and mathematical treatment are unusual, there is nothing inherently invalid in this approach. His ideas remain largely untested, but they do introduce suspension geometry and volume into consideration of the equilibrium controlling the dental arches; and whether or not his ideas ultimately prove correct, they present intriguing hypotheses for tests in the near future.

The present state of knowledge concerning form-function relationships in the oral cavity thus can be seen to concern two areas:

1. Influences on horizontal dimensions, exemplified by dental arch form and dimensions. There is no present evidence that activity during swallowing, speaking, or other oral functions is related to arch form. Resting pressures may provide the key to form-function relationships at this level.

2. Influences on vertical tooth and jaw relationships, as in open-bite malocclusion. Vertical dimension, resting jaw positions, and the effect of intermittant muscular forces on tooth eruption have not been considered carefully enough. Relationships between tongue and lip activity (as opposed to resting position) probably do exist here. They are obvious clinically, if poorly defined. The studies to date have not been designed to test the pertinent variables. Such studies continue to be needed and are within the province of both speech and dental scientists.

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DEGLUTITION: A REVIEW OF SELECTED TOPICS

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The achievement of swallow has long been recognized as a unique and fascinating performance. This complex process integrates motor performance from several cranial somatic systems and coordinates autonomic systems within the esophagus and stomach. In man, the essential physiologic mechanisms associated with swallow are impressively constant. Within the mouth and pharynx deglutition must interact with other functions: respiration, speech, suckle, etc. In these circumstances swallow dominates.

This review is concerned with deglutition. Specifically, the process by which food is moved from the mouth, through the pharynx, and into the esophagus, will be described. Particular emphasis will be directed toward a description of this process in humans. This review is not intended to be comprehensive. Thus, limited information will be presented on such topics as esophageal motility, gastroesophageal sphincter function, homologic variations in swallow performance, and the influence of taste, smell, and nutrient texture on feeding. Cogent features of deglutition relevant to speech science will be reviewed.

Detailed cineradiographic studies of oral and pharyngeal swallow mechanisms have been reported by Ardran and Kemp (1955), Cleall (1965), Moll (1965), Ramsey et al. (1955), Saunders, Davis, and Miller (1951), and Sloan, Brummett, and Westover (1964). Combined pressure and radiographic studies of swallow have been undertaken by Atkinson et al. (1957) and Sokol et al. (1966). An excellent review of oral and pharyngeal swallow mechanisms has been presented by Bosma (1957).

THE PHYSIOLOGY OF SWALLOWING

Oral-Preparatory Stage

In man, a number of oral-preparatory motions occur prior to reflex deglutition. These motions include tongue maneuvers that effect the necessary intraoral manipulations of food, buccal actions to enclose food, and molar grinding. During the preparatory stage, food is sensed for such physical characteristics as size, temperature, texture, and taste, and carried to a consistent position on the superior-dorsal surface of the tongue. Prior to reflex swallow, the hyoid is moderately elevated to its swallow-preparatory position. An arrest of oral manipulation of food, respiration, and cervical posture motions are associated with this movement of the hyoid (Shelton, Bosma, and Sheets, 1960). The bolus lies between the tongue and palate in the oral-preparatory position. An active motor mechanism consisting of elevation of the tongue and depression of the soft palate prevents the bolus from penetrating the pharyngeal airway (Bosma, 1957).

Bolus Penetration from Mouth to Pharynx

In man, where a separation of mouth and pharynx is necessitated by the requirement of maintaining patency of the pharyngeal airway (Shelton and Bosma, 1962), the patterns of movement associated with bolus penetration from mouth to pharynx are orderly and specific. The tongue forces the bolus from its preparatory position between the tongue, soft palate, and adducted palatopharyngeal folds. The bolus is compressed by a stripping wave of the tongue, whose mass is rotated posteriorly as it rests on the hyoid. The centrally grooved tongue, soft palate, and palatoglossal folds define the walls of a channel through which food enters the pharynx.

Pharyngeal Stage—Mesopharyngeal Motions

The swallow reflex occurs as the bolus passes through the palatopharyngeal partition and is forced on the epiglottis. Subsequent movement of the bolus through the mesopharynx is accompanied by an abrupt rise of the hyoid to its maximal height, elevation of the lateral pharyngeal walls, and further elevation of the soft palate now well separated from the tongue (Bosma, 1957). Passage of the bolus through the pharynx is accomplished by abrupt stripping motions of the pharyngeal musculature (Negus, 1943; Barclay, 1930; and Saunders, Davis, and Miller, 1951), and of the tongue (Ardran and Kemp 1955; Cleall 1965; Atkinson et al., 1957). During the pharyngeal stage, the palatopharyngeal isthmus closes, preventing nasal influx.

Hypopharyngeal Motions

During tidal respiration the hypopharynx is an open cavity, an artery of the respiratory system relating the nose with the larynx. The pharyngo-esophageal (P-E) spincter normally is closed as an essential feature of pulmonary respiration (Ingelfinger, 1958). The motions of the hypopharynx during swallow in man have been studied extensively (Ardran and Kemp, 1952, 1954; Barclay, 1930; Frenckner, 1948; Rushmer and Hendron, 1951; Wildman, Fletcher, and Cox, 1964). As the bolus reaches the hypopharynx the larynx is elevated to the hyoid and the floor of the P-E segment is elevated toward the larynx. Bosma (1957) stated that the final elevation of the larynx provides a skeletal reference for hypopharyngeal maneuvers associated with opening of the P-E segment. Caudal bolus transport is accomplished by orderly, sequential contraction of the tongue and pharyngeal muscles in association with relaxation and subsequent contraction of the P-E segment.

Motions of the Epiglottis

The motions of the epiglottis have been studied by Rethi (1891) and Passavant (1886). Using a creative method of marking the dorsal surface of the epiglottis with ink spots they recorded the imprints these spots made on the structures they opposed. During swallow, spots placed on the mid-dorsal surface of the epiglottis imprinted the false vocal cords, spots in a more cephalic position imprinted the arytenoid cartilages, and spots on the margins of the epiglottis imprinted the posterior pharyngeal wall. Bosma (1957) has emphasized that the motions of the epiglottis are part of the general mechanism of closure of the laryngeal vestibule, recorded radiographically as an obliteration of the laryngeal lumen. Thus, current theory holds that the motions of the epiglottis are part of a general convergence mechanism of the entire tongue-hyoid-larynx column.

Larynx Closure

In man, in whom respiration and deglutition share a common pharynx, the opening and closing motions of the esophagus and larynx are reciprocally phased. Pressman and Kelemen (1955) have reviewed these reciprocal motions. The human larynx is defended against bolus penetration by effective closure mechanisms of the aditus portion of the larynx, the false vocal cords, and the true vocal folds. Bosma (1957) has pointed out that the aditus of the larynx is derived from structures common to the pharynx. Hence, its actions are coordinated with those of the pharynx.

Pharyngo-Esophageal (P-E) Sphincter: Form and Function

Although speech scientists have demonstrated an intense interest in the mechanisms of esophageal speech, there is a sparsity of information about the form and function of the P-E segment and the esophagus in speech pathology literature. Accordingly, a selected review of these topics follows. The pharyngo-esophageal sphincter (P-E segment) is the upper sphincter of the esophagus. Anatomically, this segment is composed chiefly of the horizontal fibers of the cricopharyngeal muscle (Levitt, Dedo, and Ogura, 1965; Lund, 1965), adjacent pharyngeal muscles, and esophageal muscles (Ingelfinger, 1961). The horizontal fibers of the cricopharyngeal muscle originate on the sides of the cricoid and pass to the pharynx. The cricopharyngeal muscle has a width of approximately one centimeter and receives its motor innervation from the vagus (Code and Schlegel, 1968). Adjacent pharyngeal and esophageal muscles also participate in the total P-E sphincter mechanism and contribute to its total manometrically determined width (Ingelfinger, 1961).

Code and Schlegel (1968) have reviewed the resting-pressure profile of the P-E sphincter as defined by the "pull through" technique. In humans, a 2.5- to 4.5-cm band of elevated pressure is found (Fyke and Code, 1955; Atkinson et al., 1957; Sokol et al., 1966). Utilizing "pull through" techniques a 1-cm band of maximum pressure, appropriate in position to the cricopharyngeal muscle, has been found (Sokol et al., 1966). Resting P-E segment pressures are consistently above atmospheric, with means ranging between 18 to 60 cm H_2O above atmospheric pressure (Code and Schlegel, 1968). P-E resting segment pressures exhibit marked within- and among-subject variation.

During swallow the P-E segment must open to permit the bolus into the esophagus. A complete description of the mechanisms of P-E sphincter opening has not been developed. One feature associated with such opening, however, has been firmly established. Namely, opening of the P-E segment is associated with a marked reduction in resting segment pressure and neural inhibition of the cricopharyngeal muscle. Doty and Bosma (1956) observed inhibition of the P-E segment musculature in advance of muscle activity associated with the descending stripping wave of the pharyngeal constrictors. Code and Schlegel (1968) and Doty and Bosma (1956) have demonstrated that the P-E sphincter always opens before the arrival of the pharyngeal peristaltic wave and before the arrival of the bolus in the hypopharynx. The establishment of these anticipatory motor responses of the P-E sphincter refute the earlier conceptions of Kronecker and Meltzer (1883) and Templeton and Kredel (1943) that the bolus actively distends the sphincter to effect penetration. In fact, the upward movement of the P-E segment is opposed to the direction of the bolus. P-E sphincter closure is always associated with the termination of pharyngeal peristalsis. Closure of this sphincter is recognized by an increase in pressure above resting values, by a burst of neural impulses, and by action potentials in the cricopharyngeal muscle fibers (Code and Schlegel, 1968).

Esophageal Form and Function

Superb reviews of esophageal motility have been published by Ingelfinger (1958, 1961, 1963), Code and Schlegel (1968), Cohen and Wolf (1968), Code et al. (1958), and Kramer (1965). Anatomically, the wall of the human esophagus is composed of inner circular and outer longitudinal muscle layers. Arey and Tremaine (1933) and Treacy et al. (1963) found that the fibers of the upper portion of the esophagus (upper 2-6 cm) are striated. They are composed predominately, if not entirely, of skeletal muscle. A band of mixed fibers is found in lower segments of the esophagus. Skeletal fibers are replaced completely by smooth fibers before reaching the midpoint of the esophagus. In healthy men, resting esophageal pressure is negative: a condition reflecting negative pleural pressure. Code and Schlegel (1968) report average resting esophageal pressures (between breaths) of −5 to −6 cm H_2O. During tidal breathing, esophageal pressures increase to -12 to -15 cm H_2O during inspiration, and reverse to -1 or -2 cm H_2O with expiration.

Neural Organization of Swallow

Doty recently (1968) presented an outstanding review of the neural organization of deglutition. In his review Doty comprehensively outlined the locations of stimulation effective in eliciting deglutition in man, rabbit, cat, dog, macaque, sheep, calf, and goat. In man, Penfield and Jasper (1954) evoked swallow through stimulation beneath the temporal lobe and near the amygdaloid nucleus. Bechterew (1911) elicited swallow by stimulating the medial and intermediate portion of the same areas. Jurman (1900) elicited swallow stimulating the lateral and medial segments of substantia nigra. Bosma (1957) has emphasized that these stimulations are limited to the elicitation of swallow. He noted that the complete motor performance of swallow apparently continues as a reflex action independent of support from supramedullary areas.

In human fetuses, swallow can be elicited about the twelfth week. Respiration and suckling appear much later—about the 24th week, menstrual age (Hooker, 1952). The primitive neural development of the 12-week-old fetus suggests that control of swallow does not require prosencephalic structures (Doty, 1968). Gamper et al. (1926) and Utter (1928) have supported this hypothesis by observing normal swallow performance in human monsters with no neural tissue rostral to the nucleus ruber. Doty, Richmond, and Storey (1967), Utter (1928), and Wilson and Magoun (1945) found that the cerebellum and inferior olive make no essential contribution to the swallow process.

In his summary, Doty (1968) states that there are three separate components or neural control systems for deglutition: (1) oral-pharyngeal, (2) esophageal, and (3) gastroesophageal. These components are usually well coordinated to effect the orderly sequence of movement patterns of deglutition. Doty notes that "the intricate spatio-temporal relations of the neural and mechanical events controlled by these systems proceed in a preordained manner and can run their full course without benefit of afferent support. Indeed, the buccopharyngeal phase is almost impervious to modification by afferent action." Bosma (1957) also has stressed that once swallow has been elicited it proceeds independently from afferent modification. Doty, Richmond, and Storey (1967) have questioned the relevance of oral area proprioceptors to swallow, since the swallow reflex does not normally appear subject to significant proprioceptive modification or control.

DEGLUTITION AND: SPEECH PATHOLOGY

The need for comprehensive understanding of the basic mechanisms of deglutition by speech specialists can be demonstrated by briefly highlighting two areas of study: (1) mechanisms of air intake for esophageal speech, and (2) velopharyngeal function; and by reviewing the controversial topic of tongue-thrust patterns of swallow.

Air Intake for Esophageal Speech

The methods by which air is taken into the esophagus by laryngectomized persons using esophageal speech have been studied extensively (Diedrich and Youngstrom, 1966; Damste 1958; and Isshiki and Snidecor, 1965). Two principal methods have been described: inhalation and injection. Some investigators (Doehler, 1956) have asserted that swallowing is a form of injection. Recent investigations (Diedrich and Youngstrom, 1966; Snidecor and Isshiki, 1965; and McNally and Sheets, 1968) have shown clearly that the patterns of movement, and electromyographic and aerodynamic features associated with swallow are not observed during air intake for esophageal speech.

More recently, Weinberg and Bosma (1970) have demonstrated that the mechanisms of glossopharyngeal breathing and injection of air intake for esophageal speech are identical. Glossopharyngeal breathing is a form of intermittent, positive-pressure respiration, used by persons with respiratory paralysis. In this circumstance, the tongue functions as a principal respiratory organ and some of its motions appear, at first glance, to be similar to those observed during swallow. However, detailed study shows that the learned motor activities of glossopharyngeal breathing and air intake for esophageal speech are significantly different from, and should not be regarded as derivative functions of, swallow (Bosma, 1957).

Velopharyngeal Motions

The velopharyngeal mechanism functions to separate the oral and pharyngeal cavities from the nasal cavities during speech, swallowing, and forced, sustained inhalation and exhalation. Moll (1965) has pointed out that velopharyngeal function may not be the same during these activities. The differences in velopharyngeal activity as a function of type of task have important procedural implications for diagnosis and treatment of velopharyngeal incompetence. For example, Moll (1965) has observed that individuals with palatopharyngeal inadequacy may achieve velopharyngeal closure during deglutition, yet exhibit inadequacy during speech. Such observations emphasize (1) that judgments of velopharyngeal adequacy may vary according to activity being tested, (2) that estimates of velopharyngeal adequacy for speech based on assessments of function during swallow are of questionable validity, and (3) that the use of swallow as a therapeutic activity to develop velopharyngeal closure for speech appears questionable.

Implications

A more complete understanding of deglutition by speech specialists has led to the present-day philosophy that many of the respiratory and articulatory motions of the oral and pharyngeal areas associated with speech are not fractional derivations of swallow performance (Bosma, 1957). Moreover, the afferent-motor relationships and reflexology of swallow are probably quite different from that which exists for speech.

TONGUE THRUST: A REVIEW OF SELECTED TOPICS

A primary interest of the orthodontist is the study of muscle forces and their relationship to tooth position. Such interest highlights the time-honored quest for understanding the interactions between form and function. It has long been recognized that the teeth erupt within the muscular environment of the lips and tongue. Moreover, it has been hypothesized that the forces exerted by these muscle systems may affect tooth position. A complete understanding of form-function interactions has yet to be accomplished.

Recently, variation in swallow performance (tongue thrust) has stimulated much controversy within the disciplines of orthodontics and speech pathology. A high prevalence of tongue-thrust patterns of swallow has been reported among patients with malocclusion. Some authors have suggested that tongue thrust represents an abnormal process of deglutition, while others have described such patterns as a syndrome (Fletcher, Casteel, and Bradley, 1961). Moreover, Straub (1960) has asserted that tongue thrust causes malocclusion. In fact, some have thought that tongue-thrust swallow has such a detrimental effect on occlusion that orthodontists and speech clinicians have seriously recommended and aggressively attempted "tongue-thrust therapy" to modify such swallowing behaviors (Hanson, 1967; Gardiner, 1964; Larr, 1962; Whitman, 1962). In view of the controversy about tongue-thrust patterns of swallow, a review of available scientific information on this topic appears desirable.

General Considerations

The term *tongue thrust* appears to have been an unfortunate term, particularly when used to describe swallow performance. The term has led speech specialists and orthodontists to regard the tongue as the principal organ exhibiting deviant function during swallow and speech, and to view the tongue as the sole etiologic factor responsible for malocclusions coexisting with tongue thrust.

It is well known that the tongue is housed within a complex skeletal-dental frame. Its function is guided by various neuromuscular systems. Indeed, embryologically it is derived from oral and pharyngeal substrates. The motor behavior of the tongue is influenced by many factors. Although the various neural, skeletal, dental, and muscular systems of the head and neck are constantly interacting, the precise nature of such interactions still remains largely unspecified. In short, the tongue represents but one structure within the head and neck. Its function, like that of other oral and pharyngeal area structures and systems, may be significantly influenced by many factors. To isolate or study tongue function as an independent feature of oral and pharyngeal area morphology and physiology appears questionable.

Oral Behaviors Associated With Tongue Thrust

Tongue-thrust swallow patterns have been identified by three chief oral behaviors: (1) active or excessive contraction of the circumoral musculature, (2) absence of molar contact with associated diminution or absence of palpable contraction of the muscles of mastication, and (3) protrusion of the tongue between or beyond the incisors during swallow (Fletcher et al., 1961; Straub, 1960). Definitions of tongue-thrust swallow have been developed chiefly by comparing such behaviors with those presumably associated with normal patterns of deglutition: (1) relaxation of the circumoral musculature, (2) molar contact and active palpable contraction of the muscles of mastication, and (3) tongue motions confined within the dentition during swallow. The validity and reliability of using these oral behaviors to define normal and tongue-thrust swallow patterns in relation to occlusion has been questioned. Secondly, whether the identification of the triad of behaviors associated with tongue-thrust swallow constitutes a description of swallow abnormality also can be assessed.

Rosenblum (1963) has investigated circumoral muscle activity during swallow in 20 subjects with normal occlusion. He observed active circumoral muscle contraction in more than 50% of the swallows he studied. Ardran and Kemp (1955) have studied deglutition in a large sample of young adults by means of cinefluoroscopy. They did not universally observe molar contact during swallow, but found that frequently some individuals with no obvious facial, dental, or speech abnormalities did not bring the teeth together during swallow. Ardran and Kemp (1955) also observed protrusion of the tongue beyond the incisors in some subjects. These findings have been replicated by Cleall (1965), who observed tongue thrusting and absence of molar contact during swallow in persons with normal occlusion.

The prevalence of the three oral behaviors associated with tongue thrust also has been investigated. Data from these investigations provide insights about the merit of regarding tongue thrust as a syndrome. In a study of 500 orthodontic patients, Leech (1958) found that approximately 10% of the persons he studied exhibited tongue thrusting and active circumoral contraction, that 25% exhibited tongue thrust without circumoral contraction, and that 8% demonstrated active circumoral contraction without tongue thrust during swallow. Walther (1954) also found marked variation in expressivity of these behaviors in his study of swallow in 1000 school-age children. More recently, Subtelny, Mestre, and Subtelny (1964) studied swallow patterns in adolescents with severe Class II, Division I malocclusion. In their sample, 6% showed tongue thrust and moderate or excessive perioral contraction, 34% showed tongue thrust and little or no circumoral activity, 23% exhibited excessive circumoral activity and no tongue thrust, and 37% did not demonstrate either behavior. Subtelny et al. attempted to evaluate molar contact behavior during swallow by palpating the masseter muscle and by everting the lower lip to permit visual observation. Both methods were unreliable. Hence, efforts to evaluate molar relationships were discontinued.

Implications. Definition of tongue-thrust swallow as an abnormal pattern of deglutition or as a syndrome appears questionable. Current scientific data do not provide sufficient information for specifying normal patterns of swallow as they relate to occlusion. The differentiation between normal and abnormal and the specification of normal variation with respect to swallow performance and occlusion constitute two important areas for future research. Moreover, there is marked variation in expressivity of the three oral behaviors traditionally used to define tongue-thrust swallow. Such is the case for persons with and without malocclusion. Indeed, the reliability with which certain behaviors can be assessed clinically has been questioned. In short, an acceptable definition of tongue-thrust swallow and specification of tongue-thrust swallow as a distinct clinical entity has not been accomplished.

Tongue Thrust and Development

In embryonic life, the developing tongue is relatively large compared to its surrounding skeleton. Scott (1961) has observed this disproportionality in size between the tongue and mandible in the fetus. At birth, the mandible is also retruded relative to the maxilla (Ortiz and Brodie, 1949) and the tongue is still large (Brash, 1924). Since the teeth have not erupted in newborns, the tongue frequently occupies the space between the alveolar processes. Routine observation of newborns supports the contention that the tongue generally maintains an oral seal with the lips during deglutition.

In this regard, Ardran, Kemp, and Lind (1958a, b) have performed a classic series of cineradiographic investigations of newborn sucking and swallow behavior in an attempt to compare the mechanisms of bottle and breast feeding. They found that the tongue tip protruded well beyond the mandibular ridge during both types of feeding. Moreover, the mechanisms and patterns of movement in breast feeding were not significantly different from those observed in children who were feeding from a bottle.

The latter result is particularly important in view of Straub's (1960) assertions that (1) bottle feeding is an etiologic cause of tongue-thrust swallow and (2) tongue thrust is etiologically related to malocclusion. Straub based his etiologic contentions on observations of occlusion and swallow in patients seen in an orthodontic practice. He failed to compare his patients with a proper control group. Noteworthy in this regard are the studies of Riechenbach and Rudolph (cited in Bijlstra, 1958), Bijlstra (1958), and Leech (1958). Riechenbach and Rudolph found no significant relationship between duration of breast feeding in infancy and distal occlusion of the mandibular teeth. Bijlstra (1958) reported no significant relationship between breast or bottle feeding and maxillary protrusion in children 6 to 12 years of age. Finally, Leech (1958) could demonstrate no greater prevalence of tongue-thrust swallow behaviors in association with a lack of breast feeding.

Ardran and Kemp (1955), Ardran, Kemp, and Lind (1958a, b), Baril and Moyers (1960), and Findlay and Kilpatrick (1960) have demonstrated changes in the patterns of swallow as a function of growth and development. Their myographic, cineradiographic, and electromyographic studies show marked within-subject variation in muscle activity patterns during deglutition in normal subjects. Moyers (1962) has shown that swallow patterns change after the eruption of the deciduous teeth. The tongue may also protrude between the alveolar ridges when the incisors are missing. During the stage of deciduous tooth eruption there is comparatively rapid growth of tonsillar and adenoidal tissue (Subtelny, 1954). Encroachment on the pharyngeal airway by these tissue masses may be associated with tongue fronting postures at rest and during swallow.

During mixed dentition the discrepancy in size (1) between the jaws and tongue and (2) between the jaws may be equalized by skeletal growth. Lingual fronting may diminish as a function of this equalization. Tulley (1961) has noted that lip and tongue behaviors associated with tongue-thrust swallow frequently correct themselves (with or without orthodontic therapy) by the time the permanent teeth have erupted fully. Tulley also observed that lip and tongue function frequently adapt to abnormal skeletal-dental morphology. He discouraged the use of exercises or myofunctional therapy to modify swallow patterns, since frequently changes in labial and lingual function resulted from correction of the malocclusion itself. Hellman (1931) observed reduction in open bite with no intervening orthodontic, myofunctional, or speech therapy. Subtelny (1965) has emphasized that the tongue tip generally retrudes relative to the jaws as a function of normal growth and development.

With respect to tongue-thrust swallow, Fletcher, Casteel, and Bradley (1961) have shown that tongue thrusting during deglutition apparently varies systematically with age. The incidence of tongue thrust is higher in younger age groups (50% in 6- and 7-year-old children) than in older children (25% in 16- and 18-year-olds). Bell and Hale (1963) provide uncontrolled observations suggesting that more than 80% of 5- and 6-year-old children demonstrate oral behaviors associated with tongue thrust.

Tongue Thrust and Occlusion

There is much concern within the orthodontic discipline about the impact of muscle forces on occlusion. This concern has been stimulated by the observation of tongue-thrust behaviors in patients with malocclusion and by the underlying assumption that the muscle forces generated during these swallow performances are related etiologically to the observed malocclusion. Tongue protrusion during swallow has been thought to result in incisor protrusion, open bite, and interproximal spaces between the teeth. Subtelny, Mestre, and Subtelny (1964) observed tongue-thrust activity in approximately 50% of their sample of adolescent subjects with Class II, Division I malocclusion. Walther (1954) reported approximately the same prevalence of tongue thrusting as Subtelny et al. in subjects with Class I and Class II Division I occlusion. Moreover, Walther found tongue-thrust behaviors in 17% of a sample with Class III malocclusion. Cleall

(1965) and Ardran and Kemp (1955) have recorded tongue-thrust behaviors in subjects with normal occlusion.

With respect to occlusion, it has been hypothesized that dental arch form may be influenced by labial, lingual, and buccal muscle forces. Scott (1961) has suggested that the dental crypts acquire a definite arch form prior to the eruption of teeth. Subtelny (1965) has emphasized that bone has a definite ability to resist such forces and that bone has its own pattern of growth. Thus, dental arch form has several determinants. Likewise, tooth position is influenced significantly by many factors.

Implications. Compositely, these observations point out that malocclusion is related to factors other than muscle function (Weinstein et al., 1963; Strang and Thompson, 1958). Stated differently, tongue-thrust swallow apparently is not observed universally in patients with severe malocclusion. Oral behaviors associated with tongue thrust have been observed in subject samples exhibiting markedly heterogeneous occlusal states. Just what the identification of such swallow behaviors means to the dentist and speech specialist remains unanswered. The major research lacunae associated with these identifications lies in the interpretation of their significance. Such behaviors clearly are not universally associated with, nor etiologically related to, malocclusion. Moreover, the use of correlation statistics as evidence supporting causation between tongue-thrust swallow and malocclusion remains a questionable procedure.

Tongue Thrust and Speech

The relationships between occlusion, tongue thrust, and speech articulation represent three important variables of interest to both the dental and speech scientist. Unfortunately, limited efforts to ascertain the relationships among these three factors have been undertaken. Subtelny, Mestre, and Subtelny (1964) have made a significant contribution to this area of study. They studied occlusion, patterns of deglutition, and speech articulation in 30 adolescents with normal occlusion and normal speech, 31 adolescents with severe Class II, Division I malocclusion and normal speech, and 20 subjects with severe Class II, Division I malocclusion and defective speech (lisping). They found that subjects with severe Class II, Division I malocclusion and tongue thrust during swallow were more likely to have an associated lisp than subjects with the same type of malocclusion who did not have tongue-thrust swallow. However, the proportion of subjects with lisping was not significantly higher in the sample with tongue thrust. Moreover, 17% of their total sample with malocclusion and tongue thrust had normal speech. Similarly, 17% of their total sample with malocclusion had defective speech but did not thrust the tongue during swallow.

Attempts to relate tongue thrust and articulatory errors also have been undertaken by Fletcher, Casteel, and Bradley (1961) and Ward et al. (1961). Fletcher and his associates studied the relationship between these two variables in 1615, 6- to 18-year-old subjects. They found that tongue-thrust swallow decreased with age, whereas sibilant distortion did not. Further analysis of their data shows that sibilant distortions did not decrease with age for the sample exhibiting tongue thrust; however, sibilant distortions did decrease with age for the no-tongue-thrust group. A significant relationship (chi square) was found between tongue thrust and sibilant distortion in an analysis that combined age-levels.

Ward et al. (1961) also studied the relationships among occlusion, speech articulation, and swallow patterns in 358 children from grades one through three. The results of this study are difficult to interpret, in view of a number of inconsistencies and errors between the tabulated and text descriptions of their findings. For example, in separate places in this article the percentage of subjects exhibiting both malocclusion and tongue-thrust swallow are reported—with two different figures (91 and 44). Ward et al. did report that the frequency of articulatory errors is not as great as the frequency of malocclusion and tongue-thrust swallow. As expected, many children with malocclusion and tongue thrust did not make articulatory errors. Ward and her associates (1961) found that neither tongue-thrust swallow nor articulatory error rate decreased with age. Remarkably, they reported an increase in articulation errors for 7 of the 8 test sounds as a function of age increase. For /l/ they reported an increase of 22% in errors from the first to the third grade.

Implications. Winitz (1969) has leveled a primary criticism against the behavioral definitions Fletcher used to assess sibilant distortion. Fletcher and his associates have addressed themselves honestly to this problem. They note that the number of children reported to have sibilant errors (the percentages of /s/ and /z/ distortion at 6, 8, 16, and 18 years were approximately 19, 14, 13, and 18%, respectively) far exceeds nationally reported figures (Power, 1957; and Milisen, 1957). Aware of this fact, Fletcher et al. (1961, p. 204) write: "The frequencies of sibilant distortion . . . should not be construed to represent frequencies of children in need of speech treatment. Some of these distortions were minimal and would be noted only by a speech specialist. Therefore, the frequencies would be expected to exceed nationally reported incidence." Winitz (1969) also has emphasized the need to adhere to important experimental principles when conducting experiments of the type just described. Specifically, Winitz comments that the lack of independence between observer ratings of occlusion, speech, and swallowing (Fletcher et al., 1961) constitutes an important experimental control needed in future research.

Currently, no definitive statement can be made about the relationship between articulation errors and tongue thrusting (Winitz, 1969). The adequacy of speech as evidenced by lisping cannot be predicted on the basis of tongue-thrust swallow behaviors and associated Class II, Division I malocclusion. Although tongue thrust may coexist with defective speech, current data suggest a cautious interpretation of the strength of the observed relationships between occlusion, tongue-thrust swallow, and lisping.

GENERAL CONCLUSION: A LOOK AHEAD

Basic research is needed to specify various patterns of deglutition. Until more data are available, it seems prudent to view tongue thrust as a pattern of swallow sometimes associated with malocclusion and lisping. The current state of the art does not provide sufficient evidence for regarding tongue thrust as a cause of malocclusion or speech articulation errors. Indeed, a satisfactory description of tongue thrust has not been developed. Current data suggest that patterns of tongue-thrust swallow should not be regarded as atypical, abnormal, or representative of a syndrome.

Organized research is needed to solve these basic questions. Future investigations need to highlight two fundamental sources of interaction: (1) the effects variations in skeletal-dental morphology have on influencing adjacent muscle function and (2) the effects variations in muscle behavior have on surrounding skeletal-dental structure.

The foregoing review makes it apparent that significant research concerning tongue-thrust patterns of swallow remains to be accomplished. Moreover, there appear to be some key problems that deserve high-priority consideration. Specifically, it appears that the development of an acceptable definition of tongue-thrust swallow deserves first-priority research consideration. The definition of tongue-thrust swallow and its specification as a significant and distinct clinical entity should be developed using techniques of study that are valid, that do not influence the results, and that provide reliable observations of behavior.

Only after tongue-thrust swallow has been specified adequately and after researchers have demonstrated that tongue-thrust swallow represents a distinct clinical entity, can other important questions be investigated appropriately. Specifically, do the muscle pressures generated during tongue-thrust swallow have a significant effect on tooth position? If so, what are these effects? Can swallow patterns be altered? If so, do such modifications produce any significant changes in occlusion?

Moreover, the primary interest of dentists in tongue-thrust swallow concerns the possible consequences of such patterns on tooth position. A serious issue worthy of future discussion and clarification is the role of the speech pathologist in clinical and research activities related to tongue-thrust swallow per se. The specification of tongue-thrust swallow as a unique and significant clinical entity that influences occlusion and tooth position remains a fundamental problem for dental scientists to solve. By training or inclination, the majority of speech pathologists are not prepared to solve, or interested in solving, such questions. Given the current state of the art, a question that merits future discussion is whether the definition, clinical diagnosis and management, or modification of swallow performance per se falls within the competence, responsibility, or province of the speech pathologist, a professional whose prime concern is the diagnosis and treatment of disorders of communication.

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RESTORATIVE TREATMENT OF THE DENTOFACIAL COMPLEX

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Disorders of the dentofacial complex which require restorative treatment include cleft lip and palate, malocclusion, neuromuscular deficits, and acquired disabilities such as malignancies and traumatic injuries.

The disorder most serious in frequency and impact is cleft lip or palate. Treatment usually involves a coordinated approach by surgeons, orthodontists, prosthodontists, and speech pathologists in order to obtain optimal development of the oral structures and speech processes.

CLEFT LIP

Although some prefer to close the lip within 24 hours after birth, most surgeons perform this procedure when the patient is three months of age. This allows the soft tissues to increase in quantity and avoids any inhibiting effects on maxillary growth (Millard, 1964; Musgrave, 1964). The only argument for early lip closure is that it avoids potential psychological trauma to the parents. Closure of the unilateral lip is a one-stage procedure, while closure of the bilateral cleft may be performed in either one or two stages.

PRESURGICAL MAXILLARY ORTHOPEDICS

The use of maxillary orthopedic devices to prevent collapse of the alveolar ridge prior to lip surgery has been used only intermittently in the past. However, in the last decade these appliances have become extremely popular (McNeil, 1954). Proponents of early maxillary orthopedics have stated that the maxillary shelves, separated from the nasal septum, are deprived of the growth-stimulating action of the septum (Brauer and Cronin, 1964; Brauer, Cronin, and Reaves, 1962). However, there is real question in the minds of other investigators (Moss et al., 1968) in regard to whether the nasal septum is the principal center of maxillary growth. Other arguments for early maxillary orthopedics, such as the need to establish a sound dental arch prior to surgery (Rosenstein, 1969), improve feeding, aid speech development, and provide certain psychological advantages, also have been questioned (Pruzansky, 1964).

Pruzansky and Aduss (1964) consider that in most cleft cases good results can be achieved without resorting to early orthopedic appliances. Huddart (1962) compared patients treated with presurgical appliances with those who were not, and found no conclusive evidence that occlusion is better after orthopedics.

The statement that these appliances facilitate the feeding process is also undocumented. Since the appliance does not have a pharyngeal section, adequate separation of the nasal and oral cavities is not achieved in the posterior pharynx. Indeed, there is the possibility that the appliances may direct food to the nasopharynx in the area of the eustachian tubes during swallow. Similarly, the psychological and speech advantages of these appliances also are undocumented.

EARLY SURGICAL PROCEDURES

Primary Bone Grafting

Primary bone grafting has also been used to minimize or prevent arch contraction. Schmid, Nordin, and Johanson were apparently the first to utilize bone grafts in the treatment of cleft lip and palate (Stark et al., 1969). Scott (1959) reported that an early bone graft serves to fix the alveolar segments to the premaxilla and provides space and support for teeth adjacent to the cleft. Iliac, tibial, and rib bone have been used for these grafts. Most surgeons seem to prefer presurgical maxillary orthopedic correction prior to grafting.

The reports on bone grafting in the early sixties stressed techniques and clinical impressions, and, in general, the orthodontists and surgeons performing these procedures were optimistic about preventing malocclusion. However, Pruzansky (1964) urged caution. He stated that most cleft-palate patients could be treated conventionally without early orthopedics or bone grafting. He claimed that a mesodermal defect did not have to be repaired immediately since what may appear to be an obvious defect may become less noticable or disappear in time. Moreover, a bone graft would fix the cleft segments so firmly to each other that it would be difficult to change their positions later. Furthermore, an excessively wide cleft could be produced in the posterior region and make velopharyngeal surgery more difficult. Finally, he emphasized the surgical risks of bone grafting at a young age.

Recent studies seem to validate Pruzansky's caution. Pickrell, Quinn, and Massengill (1968) reported on a four-year study of bone grafting and found that primary rib grafts in the maxilla do not increase in size concomitant with facial growth and development. They also noted that teeth do not migrate and erupt spontaneously through the rib graft and that the graft does not form a true alveolar process. Finally, they noted that the orthopedic effect of the graft decreases as its incorporation progresses.

Similarly, Robertson and Jolleys (1968) reported that patients with grafts showed a clear deterioration in dental base relationships and developed pseudoprognathism, whereas patients without grafts had stable dental base relationships. The anteroposterior occlusion was found to be poor in the grafted group and a tendency toward poor buccal occlusion was noted. Other investigators have also reported cross-bite relationships in spite of grafting (Lynch, Lewis, and Blocker, 1966).

Stenstrom and Thilander (1967) placed bone grafts in a defect created in the premaxillomaxillary suture of the guinea pig and found that the premaxilla deviated toward the side of the defect and a marked asymmetry resulted. Since healing was not disturbed by any complications, they ruled out an inflammatory process and scarring as the causes of the asymmetry. These investigators noted that there was slight osteogenic activity at the bone ends bordering the defect and this process apparently was counteracted by the resorption in the graft. Thus osteogenic potential was greatly reduced during a period when growth is normally active. Since growth at the intact side continued at a normal rate, this probably caused the marked premaxillary deviation. Although the authors hesitate to apply these findings to humans they feel the evidence does not favor the view that bone grafting in primary cleft defects stimulates normal growth of facial skelton.

Secondary Bone Grafts

In spite of the controversy surrounding primary bone grafting, secondary grafting procedures appear to have wide support and little criticism. As Pruzansky (1964) has noted, "When the adult dentition has erupted and orthodontic treatment completed at about age 13, it becomes possible to determine whether the individual is indeed deficient in tissue mass at the alveolar process."

Results of secondary grafting have been good in terms of improving arch stability and occlusion, although the procedure is not utilized very often. Resorption of tissue appears to be minimal.

Palatal Surgery

The palatal defect is usually closed surgically at 12-18 months of age. However, there is wide disagreement regarding the optimal time for closure. Operation at one year of age permits repair of the palate at the time of early speech development. Although advocates of early closure believe it prevents harmful, compensatory movements from developing there is no evidence that this is true. Indeed, a recent study of Drexler (1968) suggests that there is no relationship between age at surgery and the speech variables of nasality and articulation proficiency.

Proponents of delayed closure have argued that early closure necessitates surgical undermining of palatal periosteum. They consider that maxillary growth is impeded as a result of impairment of the subperiosteal blood supply to the bones of the middle third of the face (Stark, 1964).

A number of animal studies have been designed to yield basic information on the effects of specific surgical variables on skeletal growth of the face (Kremenak, Huffman, and Olin, 1967). The findings suggest that the surgical variable most responsible for asymmetry in growth was that involving denudation of the palatal shelf bone just medial to the alveolar process.

In comparison, studies of human unoperated cleft-palate skulls indicate that the general development of the facial bones is good except for the region of the cleft (Atherton, 1967). A small deficiency in width of the shelf, length of the maxilla, and vertical development of the canine teeth were noted in the cleft area.

Hotz (1969) proposed that surgery should be delayed until 80% of maxillary development has occurred, that is, at least age 5-6 but preferably 7-9. She utilizes a maxillary orthopedic appliance pre- and postoperatively to guide the development of the maxillary arch. Hotz also reported no difference in speech proficiency among patients whose palates were closed early or late.

Bernstein (1968) studied the effect of timing of the cleft operation on maxillary growth and concluded that the optimal time for repair is between 30 and 36 months of age. He indicated that growth of the maxilla and development of the midthird of the face are materially altered if the palatal operation is performed before the deciduous molars are in occlusion, namely, before 24-30 months of age. Coccaro and Pruzansky (1965) performed a longitudinal study of the skeletal and soft-tissue profile in children with unilateral cleft lip and palate and came to different conclusions. They stated that earlier reports relating to the deleterious effects of surgery on the growth of the middle face did not apply to the subjects in their study. The difference in findings stems from the fact that surgical techniques have changed and the procedures currently used do not inhibit the growth process. Since palatal repair for most of their patients was completed before age 2½, they suggest that age at time of surgery is not a critical factor affecting growth.

EARLY ORTHODONTICS

Many orthodontists are inclined to treat cleft-lip and -palate patients at an early age, in the belief that establishing a more normal oral environment will promote more normal jaw growth. The effects of early treatment have been studied by means of cephalometric radiographs (Ross and Johnston, 1967), and it appears that it is beneficial for children with bilateral cleft lip and palate. However, for most children with unilateral cleft lip and palate, orthodontic treatment prior to the permanent dentition has no specific effect on the facial growth pattern.

In contrast, some clinicians feel that treatment in the mixed dentition state is beneficial since major problems can be alleviated to some degree.[1] For example, a patient with a cross bite, whose mandible is in a convenience bite

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[1] Smiley, G. R., personal communication (January 1970).

resulting in facial asymmetry, may have abnormal condylar growth. Early treatment would prevent this.

PALATOPHARYNGEAL INCOMPETENCY AFTER PRIMARY SURGICAL CLOSURE

The actual frequency of palatopharyngeal incompetency is difficult to determine. At the present time, it seems that information about incidence is reported only in connection with other findings. These various reports make it possible to present some information on the frequency with which the condition occurs, but should be considered tentative. It seems that the group of individuals with palatopharyngeal inadequacy following primary cleft palate repair continues to be sizable. Nylen (1961) presented data summarizing the results from several centers and noted that speech improvement after cleft palate repair ranged from only 62% to 100%. Williams and Woolhouse (1962) reported that 20 to 40% of patients with palate repair are left with palatopharyngeal insufficiency.

If palatopharyngeal incompetency remains after primary closure, secondary surgical procedures are usually attempted or a cleft palate prosthesis is fabricated. In most cases surgery is the treatment of choice, unless the defect is large and there are missing teeth which require prosthetic replacement.

SECONDARY SURGICAL PROCEDURES

The surgical procedures may be classified into four main groups: (1) lengthening the palate, (2) pharyngeal flaps, (3) pharyngoplasty by muscle transposition, and (4) retropharyngeal implantation of autogenous or exogenous implants.

Lengthening procedures of the palate often have been disappointing because of contraction of the scar. Usually this operation is accompanied by a pharyngeal flap to prevent this. Modifications to minimize contractions of the raw nasal surface also are becoming standard procedure (Cronin, 1957).

The pharyngeal flap is favored by most surgeons for treatment of palatal incompetency after primary closure. There are many variations, but the two most frequently used are the inferior and superior based flaps. The superior based flap is usually preferred and considered to provide the best speech results. Although electromyographic techniques have shown (Li and Lundervold, 1958) that the muscles in the flap survive as active contractile tissues, its success for speech purposes depends largely on the mobility of the lateral and posterior pharyngeal muscles. Bzoch (1964) reported on the speech of 40 cleft-palate patients with pharyngeal flaps and found that although hypernasality can be eliminated, hyponasality may be introduced. This may diminish in time, however, as the flap decreases in size.

Moll et al. (1963) presented data on 123 subjects with pharyngeal flaps and concluded that the etiology of the problem did not appear to be related to the success of the flap. Flap width appeared to be an important factor in successful results. Presumably this enables the lateral pharyngeal walls to make contact more easily. The Iowa group (Moll et al.) also found that age at the time of the surgery was related to success of the procedure. Less successful results were obtained with individuals over 15 years of age. Other clinicians have noted this also. The reason is not known, but it may be related to established habit patterns and muscle function.

Recently some surgeons have reported using the pharyngeal flap as a primary operation with palatal closure in one-year-old infants. (Stark et al., 1969). They report that patients achieved average or better speech after this procedure. Most surgeons hesitate to use this approach because of possible interference with the eustachian orifice, although no increase in middle ear disease has been reported. The main criticism appears to be that the flap procedure is unnecessary in many instances.

Pharyngoplasty

Pharyngoplasty reduces the size of the pharyngeal cavity anteroposteriorly and laterally. This procedure provides adequate velopharyngeal closure when the palatopharyngeal gap is small and the velum is quite mobile.

Retropharyngeal Implants

The use of substances to fill the posterior pharyngeal space was advocated as early as the turn of the century. Paraffin, bone, and fascia have been used in the past; but instability, tissue reactivity, and embolism have been frequent problems.

Some surgeons are using cartilage implants in the posterior pharyngeal wall, and achieving apparently good palatal closure in selected patients (Hess, Hagerty, and Mylin, 1968). Similarly, teflon is also used to diminish the velopharyngeal gap (Bluestone et al., 1968; Ward, Goldman, and Stoudt, 1966). Usually the material is injected into the posterior pharyngeal wall. This procedure has achieved a fair degree of success in cases of borderline incompetency. Palatal and lateral wall movements are necessary prerequisites for success. The technique can be dangerous, however, if the material is injected into the wrong site. The use of teflon also has been proposed for incompetency developed after adenoidectomy.

CLEFT PALATE PROSTHESES

There are three types of prosthetic speech appliances and they differ primarily in the design of the posterior section. The static type is the most frequently used and simplest to construct. The hinged appliance is designed to simulate palatal movement but does not offer any advantage in achieving velopharyngeal closure. The meatus appliance is designed to block the nasopharynx except for a small opening. The indications for its use are questionable.

The primary function of the prosthetic speech appliance is to insure adequate velopharyngeal valving for socially acceptable speech (Mazaheri and Millard, 1965; Warren, 1965). Although the pharyngeal section of the appliance is designed to contribute to oronasal separation during velopharyngeal closure, it also must allow nasal emission of air during phonation of nasal consonants and during breathing. The success of the appliance depends to a great extent upon the mobility of the lateral and posterior pharyngeal walls. Thus, its function is similar to that of a pharyngeal flap but it has a distinct advantage in that it can be made larger or smaller as the need arises. The posterior section usually is placed in the area of maximal lateral and posterior pharyngeal wall activity, as this minimizes its size. Usually this is slightly above the atlas bone in the nasopharynx.

Studies have demonstrated that speech performance is significantly improved by obturation, although normal intelligibility and voice quality may be difficult to attain in older patients (Subtelny, Sakuda, and Subtelny, 1966). The appliance is usually less successful when the palate is long and immobile or where a long-term speech disability exists. However, if adequate velopharyngeal closure is obtained, speech usually is improved to within normal limits.

It is interesting to note that a number of clinicians have reported that complete separation of the oral and nasal cavities is not essential for good speech. However, it appears that the opening should be less than 0.2 cm^2 during plosive and fricative sound production (Warren, 1965). Conversely, studies have shown that if the pharyngeal section is too large, denasal voice quality results. The data indicate that the opening for nasal consonants should be 0.2 cm^2 or more and this opening should begin before or during the vowel production preceding the nasal consonant (Warren, 1965).

Prosthetic speech appliances also appear to have a stimulating effect upon muscle function. Clinicians frequently note the need for reducing the size of the pharyngeal section within a few months after insertion of the appliance. Apparently, lateral and pharyngeal wall muscle function improves. This has led to the fabrication of speech-stimulating appliances for selected patients (Blakeley, 1964; Shelton et al., 1968). The pharyngeal section of these appliances is reduced over a period of time in order to stimulate the pharyngeal muscles to greater activity. Often this is done prior to a pharyngeal flap procedure. Results are good when the velopharyngeal gap is small or when there are no neuromuscular deficits.

Temporary prosthetic speech appliances also have been used for diagnostic purposes in instances where there appears to be neuromuscular involvement (Curtis and Chierici, 1964). The potential effect of a pharyngeal flap often can be judged by the success or failure of the appliance. Appliances also have been used with some success in cases where a flap has failed due to minimal lateral wall activity. The purpose of the speech aid in this instance is to stimulate muscle movement and determine whether the flap should be enlarged or removed.

TREATMENT OF VELOPHARYNGEAL INCOMPETENCY DUE TO NONCLEFT CONDITIONS

Many individuals with palatopharyngeal insufficiency without cleft palate consult cleft palate programs for treatment, and therefore some information about them is available from cleft palate centers. Smith et al. (1963) reported a group of patients having pharyngeal flap surgery, 30% of whom had palatopharyngeal insufficiency not associated with repaired cleft palate.

Removal of adenoid tissue is sometimes cited as a cause of palatopharyngeal insufficiency. In connection with this, Gibb (1958) provides some information regarding the frequency with which hypernasal speech follows adenoid removal. He reported that 19 children in 27,754 developed hypernasal speech after tonsil and adenoid surgery, for an incidence of 1 in 1450 surgical cases. Since individuals who have tonsil and adenoid surgery may not be entirely representative of the general population, it is not logical to conclude that this information represents the occurrence of palatopharyngeal insufficiency in the general population. However, it is clear from the Gibb data that any individual surgeon is likely to have extremely limited experience with hypernasal voice quality in patients following tonsillectomy and adenoidectomy. Also it is interesting to note that all cases of hypernasal voice reported by Gibb were between the ages of three and eight years.

Greene (1957) has supplied additional information from a group of 377 children examined before tonsillectomy and adenoidectomy. She noted the voice disorder of hoarseness as well as articulation problems associated with hearing loss and malocclusion prior to surgery. After tonsillectomy and adenoidectomy, 25 of 347 children demonstrated nasal escape of air. In the remaining group of 30 who had adenoidectomy only, three developed gross nasal escape. This nasal escape was of short duration (four to six weeks) in all but four cases.

Submucous cleft of the palate is a condition that frequently is responsible for palatopharyngeal insufficiency. The degree of the defect in the hard palate may vary from a slight notching to a large U-shaped absence of bony tissue. In the soft palate, the defect may vary from a bifid uvula to a complete lack of union between the muscles at the midline of the entire soft palate. A submucous cleft may result in shortening of the anterior-posterior dimension of the hard or soft palates. The increased distance, along with the lack of muscle connection in the soft palate, usually accounts for the lack of palatopharyngeal function in individuals with submucous clefts.

Another congenital condition associated with palatopharyngeal insufficiency is paresis of the soft-palate mucles. This is best described by Worster-Drought (1954), who labeled it *congenital suprabulbar paresis*, and stated that ". . . the impaired development is confined to the suprabulbar neurones, that is, the pyramidal tract nerve fibers above and proceeding from the motor cortex of the brain to the cranial nerve nuclei of the medulla or bulb which supply the muscles of articulation." He indicated that the mildest form is an isolated paralysis of the soft palate, but that in its more severe form it may affect the tongue, lips, soft palate, and laryngeal and pharyngeal muscles. Histories of such individuals indicate that voice quality was hypernasal from the time they began to speak. Articulation errors indicative of poor palatopharyngeal closure are evident also.

Many of the specific conditions described as causes of palatopharyngeal insufficiency may be considered under the general heading of regional growth disturbances. Fletcher (1960) described ten individuals who illustrate this category. His findings on these subjects included such specifics as (1) abnormally obtuse basicranial angle; (2) unusual origin and insertion of the levator veli palatini muscles; (3) large anteroposterior dimension of the pharynx at the level of the hard palate; (4) bifid apex of the odontoid process; (5) reduced linear and vertical dimensions of the soft palate; (6) tongue impairment in maneuverability; and (7) imperfections of the teeth (dentinogenesis and amelogenesis imperfecta). His study suggests that regional growth disturbances in various combinations are associated with hypernasal voice quality and, therefore, with poor palatopharyngeal function. However, in some individuals the movement of the soft palate is sluggish or seems to occur after the sound has passed into the nasal cavity. The result is hypernasal voice quality and weak production of certain consonants.

The importance of determining whether palatopharyngeal insufficiency is congenital in origin relates to treatment procedures (Bradley, 1970). If it is congenital, the individual usually has poor speech from the beginning, and to attain normal speech he may require different treatment from that of the individual who acquired palatopharyngeal insufficiency later.

Acquired Conditions

Perhaps neurologic disorders account for the largest number of acquired conditions causing palatopharyngeal insufficiency. Randall, Bakes, and Kennedy (1960) concluded that these could be divided into disorders of upper motor neuron, nuclear, peripheral nerve, or end organ.

Another important cause of acquired palatopharyngeal insufficiency is pharyngeal or palatal carcinoma, which may require surgical removal of portions of the palate or pharynx at any age. Restoration of the missing structures with functional prostheses usually results in normal speech. Rarely, speech training may be necessary to assist the individual in adjusting to the prosthesis. Palatopharyngeal insufficiency from trauma, through accident or other causes, is similar to that resulting from carcinoma.

Surgical removal of adenoid tissue already has been mentioned. Fletcher (1960) proposed that removal of the adenoid tissue simply unmasks a regional growth disturbance that was previously present. Roberts (1960) indicated that removal of adenoids may create a nasopharynx larger than normal so that palatopharyngeal inadequacy occurs without any other defect. He also mentioned that trauma to palatal and pharyngeal musculature during adenoidectomy may destroy the sphincter-like action of the mechanism and result in incomplete palatopharyngeal closure. Gibb (1958) suggested that removal of the adenoids deepens the pharynx, and that nervous upset due to the operation may cause hysterical hypernasality. Greene (1957) found emotional upset in only 4 of 377 children who underwent tonsillectomy and adenoidectomy. The evidence is sufficient to suggest that some cases of palatopharyngeal insufficiency are first noted after the removal of adenoids.

Treatment of palatopharyngeal incompetency arising from noncleft conditions has been extremely difficult, especially where there is neuromuscular involvement. The techniques of surgery and prosthesis depend upon good lateral and posterior pharyngeal wall function, and this usually is not present. Hardy et al. (1969) reported on management of velopharyngeal dysfunction in cerebral-palsy patients and found that surgery was successful in only 3 of 6 cases. Speech improvement was not sufficient to consider that procedure worthwhile. In comparison he found that prosthetic management with palatal appliances and traditional speech aids achieved greater success. Speech usually improved immediately after insertion of an appliance. Ten of eleven patients treated prosthetically were judged to have improved. However, the authors felt that a prosthetic program probably would be of minimal assistance to the severely handicapped child whose tongue, lips, and jaws manifested extreme restrictions of mobility.

A new surgical approach using muscle transplants has been reported recently (Kiehn et al., 1965). The aim of the procedure is to provide kinetic energy to stimulate function. The technique involves a fascial graft attachment of the temporalis or masseter muscles to the nonfunctioning palate. The best results have been obtained in patients with paralyzed palates. This appears to offer some promise for the patient with neuromuscular deficits where results to date have been extremely poor.

In cases of palatopharyngeal incompetency due to myasthenia gravis, improvement has been noted after administering drugs prohibiting the destruction of acetylcholine (Wolski, 1967). Perhaps investigations in cytogenetics and biochemistry may reveal the etiology of a number of conditions causing palatopharyngeal insufficiency which might respond to medication.

Malocclusion

Although fricative sounds are articulated through the teeth, even severe malocclusions need not necessarily cause disorders of speech. Most individuals apparently can compensate for anatomic deficiencies. Individuals with dental malocclusions more frequently speak with lisps than do those with normal teeth. Sixty to 70% of speakers with lisping errors have dental malocclusions, whereas only 25% of normal speakers have dental deviations (Snow, 1966). Jensen (1968) studied the relationship between the anterior teeth and speech and found that tongue and lip patterns were adapted to some extent to compensate for abnormal anatomical relationships.

Severe underdevelopment of the maxilla due to cleft palate crowds the tongue but this in itself adds only a small component to the complex speech disorder observed in many of these individuals. For example, an open bite alone usually does not distort speech. However, if it occurs in the presence of palatopharyngeal dysfunction, this dental deviation compounds the overall speech problem.

Orthodontists consider the functional environment to be an important etiologic factor in malocclusion. Ricketts (1968) has reported malocclusion produced by tonsillar and adenoidal obstruction of the upper pharynx. He found that dental arch stability is enhanced when normal nasal breathing and swallowing are achieved after tonsillectomy and adenoidectomy.

Typically, the patient with respiratory obstruction syndrome displays crossbite, open bite, tongue thrust on swallowing, and mouth breathing.

Tongue-Tie

Tongue-tie is a condition in which the lingual frenum is short, thick, and fibrosed. When the condition is severe enough to limit free motion of the tongue tip, open bite malocclusion and mandibular prognathism may result. Except in rare instances tongue-tie is not thought to cause speech problems, although it may contribute to difficulties in speech rate. Excision of the thickened frenum, division of the fibers of the genioglossus muscles, and closure of the wound with z-plasties result in permanent correction of the ankyloglossia (Horton et al., 1969).

FUTURE RESEARCH NEEDS

This review has presented a number of areas in which further research is indicated and I will attempt to summarize a few of these.

Cleft-palate speakers often develop compensatory patterns of articulation as a result of palatal dysfunction. Some individuals develop Passavant pad activity and lateral pharyngeal movements, others do not. Pharyngeal fricatives, glottal stops, or nasal grimaces may occur. In others there may be an increased frequency of palatolingual contacts or lateral lisping. Some individuals increase respiratory effort, others decrease it. In certain situations compensatory adjustments improve speech performance and in other situations they do not. There is little information concerning how and why these adjustments occur, that is, under what situation a compensatory response develops and, importantly, whether the specific response is beneficial or detrimental to the individual. There are some desirable responses, such as increased lateral pharyngeal wall activity, which are beneficial. What techniques or procedures are capable of developing and improving adjustments such as increased muscle activity? Can we establish some criterion which will help to establish the limits of achievement? These are essential questions requiring our immediate attention.

Proponents of early palatal surgery base some of their arguments on the need for an intact, functioning palate prior to speech onset. They suggest that this prevents deviant speech and swallowing patterns. However, documentation is lacking.

Some orthodontists propose that early appliances stimulate oral function, but, again, no data are provided to support this contention. Patients with anterior malocclusions must compensate with their tongue, lips, or jaws for adequate fricative production. Do tongue tip adjustments increase the possibility of lateral lisping? Similarly, studies on effects of interceptive treatment on growth need to be continued.

The use of muscle transplants to provide motion to paralyzed structures is a promising area of surgical research, and evaluative studies will be necessary as the technique becomes refined. In addition, new developments in surgery will require further evaluation of their effects on orofacial growth.

Maxillofacial prosthodontics is a rapidly developing specialty. Greater emphasis on research for the fabrication of better substances to simulate orofacial tissues is desirable. Materials should be more lifelike, longer lasting, and not harmful to the tissues they contact.

Among the most exciting contributions of modern genetics to the understanding of inherited disease have been studies of the manner in which the essential genetic information coded in the DNA of the gene regulates the synthesis of protein and enzymes, and studies of the mutations which cause defects in protein structure and biochemical pathways. As our knowledge increases regarding the exact chemical errors in genetic disease, therapeutic measures for alleviating the deleterious consequences of biochemical defects can be designed. Recently several hereditary conditions with associated defects in speech and other oral functions have been described. These may be examples of the biochemical types of disease that soon will be treatable.

We know little about these specific diseases, and there exists a strong possibility that other speech, oromotor, and hearing defects may be attributable to biochemical disorders. A thorough understanding of the location of, and subsequent alterations caused by, possible biochemical blocks may provide a rational therapeutic approach to treatment.

An attempt has been made in this paper to evaluate the past and current work in restorative treatment of disorders of the dentofacial complex. Some areas of future research are suggested, but these represent only a few of the many gaps in our understanding of fundamental problems. The essential point is that there is a critical need for intensified research in the clinic as well as in the laboratory. The success of the total effort by surgeons, dentists, and speech pathologists will depend to a great extent upon cooperation and dialogue. These efforts, we hope, will lead to newer and more successful approaches to patient care.

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MODIFICATION OF ORAL-FACIAL FUNCTION DURING SPEECH

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Our presence at this workshop signifies that each of us is performing work pertinent to oral-pharyngeal form and function. Patients with disorders such as cleft palate and dental malocclusion form the basis of our common interests. We recognize that if our fields are to serve these patients we must understand normal and disordered phenomena related to speech and dental development. Therefore, we have sought information regarding the anatomy and physiology of normal and disordered oral structures and functions. Then, in seeking to understand variables and relationships that have been identified, many of us have turned to the study of the elements of which these phenomena are composed. Developments in speech science have contributed to understanding speech production and perception, and we hope that reductionistic biological research will lead to prevention of the disorders that trouble us.

My purpose, however, is not to plead for basic science but to argue for application of scientific methodology to the investigation and development of the treatments that we provide to patients. Better speech therapy may result from improved understanding of speech production. For example, knowledge about how the articulation of one phone influences the movements used in production of a neighboring phone (Daniloff and Moll, 1968) may lead to the identification of speech contexts that will facilitate the acquisition of a specific articulatory skill (Shriner, Holloway, and Daniloff, 1969). However, treatment applications will occur only if someone uses the speech production research in the formulation and testing of new treatments. This requires research as careful and complex as that involved in basic research. Basic knowledge by itself will not solve our applied problems. Good clinical work cannot be founded on pronouncements whether delivered by scientists or senior clinicians.

In this essay, tongue thrust and palatopharyngeal closure are discussed with reference to their remediation by behavioral clinical treatments.[1] The evaluation of behavioral treatments administered to patients is emphasized because dental-

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[1] Many dental treatments and essentially all speech pathology treatments are behavioral in nature. A dental treatment intended to influence the way a patient positions or moves oral structures even after the treatment is terminated would fit this category. An example is the use of crib devices to alter tongue behavior.

speech literature concerning behavioral treatments, especially in the area of tongue thrust, often lacks a research foundation, reflects poor choice of research procedure, or shows misuse of the satisfactory procedures that were employed. Other topics include articulation disorders and the difficulty of identifying causes of existing disorders.

EXPERIMENTAL ANALYSIS OF BEHAVIOR

When we attempt to study a clinical treatment with experimental precision, we immediately find that we can't locate homogeneous groups of subjects to sort by true random methods into experimental and control groups (Spriestersbach, Moll, and Morris, 1964). Even if we could find hundreds of suitable subjects, we often would not be able to use them all because of personnel, equipment, and space limitations. Furthermore, thorough study of an individual or of a small sample of subjects is often sufficient and sometimes essential to solution of the problem being investigated. There is a need and place for extensive study of individuals and small groups. This requires the experimental expertise that permits the identification and assessment of phenomena, and is to be distinguished from contemplation of the day's work in the clinic.

Among persons concerned with the experimental modification of behavior, some have focused on research methods derived from operant psychology. They have formed a society and publish at least two journals. One, the *Journal of the Experimental Analysis of Behavior*, is directed to studies involving the behavior of individual organisms. The other, the *Journal of Applied Behavior*, publishes studies that apply behavioral analysis procedures to the solution of problems having social importance. The experimental analysis of behavior (EAB) procedures that these workers use can be applied to the assessment of dental-speech treatments. I wish briefly to describe and comment upon those procedures because they require the investigator to look closely and frequently at his treatments and at the behavior of the subject or patient to whom they are directed.

EAB involves intensive study of the responses of individual subjects to experimental treatments. The independent or treatment variable and the dependent variable are precisely defined. Then the treatment is evaluated by measuring the dependent variable under baseline, treatment, and extinction conditions. A treatment effect is shown when the dependent variable measure departs from a stable baseline following initiation of treatment and returns toward the baseline during the extinction period. The experimenter may seek reversal of performance as he repeats treatment and extinction conditions alternately (Baer, Wolf, and Risley, 1968). Confidence in the treatment is greater if a measure of a third variable not subject to treatment is stable on its baseline during the course of the study. The third variable in this multiple baseline procedure is selected according to knowledge about the phenomenon under study. Replication studies are also an important part of this work (Sidman, 1960; Bachrach, 1965).

EAB procedures have had little application in dental-speech research to date. Moller, Starr, and Martin (1969) applied them to the treatment of facial grimacing in subjects with cleft palates. Base rate for facial grimacing was established by determining the number of grimaces during each of three consecutive two-minute talking periods. During treatment, the word *wrong* was presented to the subject after every fourth grimace. Over the course of treatment, the frequency of grimace was reduced to 40% of base rate. Termination of treatment was followed by a return to 90% of the grimace base rate. The authors' definition of treatment and response through design and instrumentation permitted evaluation of the treatment. This particular treatment would be appropriate for persons who continue to demonstrate a facial grimace after satisfactory treatment of palatopharyngeal closure, if the freedom from grimace can be made automatic. However, in my opinion, the treatment may be contraindicated in persons whose palates have not been well treated. Such individuals might respond to the treatment by means of harmful compensatory adjustments. This concept, of course, requires further evidence.

Certain criticisms may be made with reference to EAB practices. While Moller, Starr, and Martin are well informed about cleft palate, some persons have applied EAB methods to complex problems about which they know little. However, as this movement matures, we see persons trained in EAB methods becoming expert in the content areas in which they apply their methods. Also, experienced workers in a given area may adapt operant derived methods for their own purposes.

In EAB research, conclusions are often based on visual inspection of a data plot. Commonly, time is plotted on the abscissa and the dependent variable on the ordinate. The choice of intervals used in plotting presents a problem. The values and spaces used on either axis can influence the interpretation of the data.[2] Use of logarithmic paper facilitates the plotting of measures that range widely. It is also useful in recording more than one variable on a single piece of paper.

Much emphasis has been placed on the rate of occurrence of various phenomena as the dependent variable in operant research. For example, an experimenter might undertake to influence the number of words a retarded child produces in a given period of time in a specified situation. Sometimes rate is studied when other aspects of the behavior, for example response magnitude, would seem to be more important. Many studies of speech rate, for example the work of Lass (1968; see also Lass and Noll, 1970) have not involved EAB methodology.

Some EAB investigations have used poor dependent variable measures. As in other research procedures, the dependent variable measure used in a study requires development through research. Other procedural problems can also distort results. Thus, orderly shifts in the dependent variable during the course

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[2] O. R. Lindsley, personal communication.

of a study may reflect a functional relationship between stimulus and response. But they also may be a function of experimenter error.

Some of the problems I mention are not unique to EAB. The behavioral analysis movement will continue to contribute to methodology needed for the study of treatments. EAB principles and procedures have been reviewed in the speech literature by Brookshire (1967), Spradlin and Girardeau (1970), and by others cited in their references. I'll leave further discussion of the topic to those experts. Let us turn to other research principles that have been developed over the years and that continue to be important to us.

OTHER RESEARCH METHODS

Use of experimental methods in the behavioral sciences antedates the operant movement, and methods and measurements in addition to those identified with the EAB school can be applied to individuals (Chassen, 1967). Indeed, group research can be viewed as a collection and combination of studies of individuals (Moll, 1963). Underwood (1957, Chaps. 2-4) described various jobs to be accomplished by science. One is the identification of phenomena and their definition through measurement. A second is the investigation of relationships among phenomena. This work is facilitated by use of correlational statistics. These statistics cannot demonstrate cause and effect relationships (Perkins and Curlee, 1969).[3] A third job for research, also discussed by Underwood, is the definition of relationships in the situation wherein one variable is manipulated, additional variables are controlled, and yet another variable is tested for change. The term *experiment* is sometimes reserved for work of this type. Causation statements are perhaps best founded on experimental manipulation whether we're dealing with groups or with individuals.

We may demonstrate the effectiveness of a treatment through use of experimental manipulation, but how can we identify the etiology of something that already exists? We are not free to create the disorder that concerns us. Sometimes investigators identify two groups and then attempt to account for differences between them in terms of their histories. This ex post facto research may lead to the identification of variables for further research. However, the possibility of confounding variables is so great that the method is not well regarded (Underwood, 1957, pp. 97-99).

Underwood (1957, pp. 112-123) does describe a kind of research program that may permit inference of causation from comparison of subject groups and from use of correlations. The causation inference, however, must be compatible with well established generalizations and must support predictions. Let me give an example. In attempting to determine the etiology of a given behavior—say,

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[3] The fact that a correlation between two variables does not indicate causation is well accepted. Some investigators, however, seem willing to draw etiological conclusions from comparisons involving *t*-test analysis. Unless the study design involves a treatment condition, the use of the *t* test, like the correlation coefficient, will just tell something about the relationship between two variables.

articulation errors—an investigator divides subjects into groups with reference to that behavior. Given, then, a good articulation group and a poor articulation group, the investigator compares the groups with reference to a second variable—say, occlusion. If the groups are found to differ on the second variable, then new groups are found that again differ on the original articulation variable. This time, however, the groups are matched on a third variable—say, tongue thrust—that is thought to be related to the second or occlusion variable. If the good and poor articulation groups that are matched for tongue thrust do not differ in occlusion, then we would conclude that tongue thrust bears a more important relation to articulation adequacy than does malocclusion. However, before causation could be claimed, additional variables would have to be studied in this manner. Perhaps sensory function, genetic factors, age, articulation, and other variables would be important. A series of investigations interpreted with reference to established principles could establish an etiology hypothesis. The hypothesis should then be used to test further predictions. All this, however, would not demonstrate or guarantee the effectiveness of any treatment.

Cattell (1966, pp. 22-23) discussed demonstration of etiology on the basis of time relationships among variables. The multivariate designs discussed in the Cattell book involve use of several independent and dependent variables in a single study. Such designs would be more efficient and accurate than the procedure described in the paragraph above. We may anticipate more frequent use of multivariate designs in research pertinent to dentistry and speech pathology.

TONGUE THRUST

Let us consider briefly the kinds of research that have been done in the area of tongue thrusting. To what extent have variables been identified and defined, relationships investigated, and experimental studies performed? Much of the literature on tongue thrust[4] is concerned with the definition of variables and the study of relationships among them. Particular attention has been paid to articulation and occlusion as they relate to tongue thrust. We think that the incidence of tongue thrust is high and that many people with this problem also demonstrate articulation errors and malocclusion. However, the relationships among these variables are far from invariant and the term *tongue thrust* lacks unitary meaning. Marks (1968) compared children with cleft palates and children without for incidence of tongue thrust and for interdentalization during the production of linguodental or linguo-alveolar phonemes. She found a greater incidence of each phenomenon in the subjects with clefts. However, her data give little information about magnitude or consistency of interdentalization. Nor are we given information about subject variables within the cleft-palate sample that may be related to tongue thrust or interdentalization. Perhaps these

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[4] See, in this *Report*, "Processes and Maturation of Mastication and Deglutition," by Fletcher; "The Tongue and Oral Morphology: Influences of Tongue Activity During Speech and Swallowing," by Proffit and Norton; and "Deglutition: A Review of Selected Topics," by Weinberg.

phenomena are related to cleft classification, age, maxillary arch defects, or other variables.

Winitz (1969, pp. 171-174) reviewed and critized some of the tongue-thrust literature as it pertains to articulation. His review supports the position that the need for definition and relationship studies has not been completely satisfied. Experimental studies that would support treatment claims have not been done.[5] Clinical reports that support etiological claims tend to have ex post facto components. A finding that the case histories of persons who engage in tongue thrusting differ from the histories of persons who do not, must lead us to wonder why as children they were treated differently in the first place, if indeed they were. Subtelny (1965) pointed out that "to date it has not been conclusively shown by controlled research studies that re-education of swallowing activity will, by itself, effect an appreciable improvement in malocclusion and/or defective speech production." Bloomer (1963) comments on the probable heterogeneity within the population of persons termed tongue thrusters. Hoffman and Hoffman (1965) wrote that various physiological conditions can lead to tongue-thrust behavior. The phenomenon may be normal behavior in some situations and not in others. They state that it is difficult to influence reflex behavior through training and that since "swallowing is almost entirely reflex in nature" the prognosis for change with therapy may be poor. Since their article was published, however, conditioning has been found to influence various autonomic functions that once would have appeared to be less subject to influences of training than are swallowing reflexes (Miller, 1969).

In 1962, Palmer called for research to provide a basis for resolving arguments about tongue thrust. It is now 1970, but we continue to have more arguments than evidence in this area. I'm afraid that too many treatment viewpoints concerning tongue thrust are based on relationship studies, ex post facto comparisons, or on clinical experience wherein the clinician observed one or two of a multitude of variables and concluded that the two were responsible for a poorly

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[5] I've read an unpublished manuscript reporting Newman's (1969) thesis research. He reported changes in cephalometric measures made before and after his subjects were oriented to exercises intended to "improve the tone, coordination, and development of the masticatory muscles." Conclusions based on this study must be speculative, since the treatment was not controlled or supervised by the experimenter and no control group was employed. Perkins (in press) cites a dissertation by Stansell (1969) wherein two behavioral treatments were compared for influence on occlusion. The dissertation was not available from University Microfilms at the time this was written. Stansell administered swallow training and sigmatism correction intended to keep the tongue away from the incisors. According to Perkins, "Stansell found that sigmatism training reduced dental overjet regardless of tongue thrust swallow, whereas deglutition training alone was not as effective."

The report of Stansell's results is surprising, since the tongue exerts more pressure during swallow than during speech. It would be interesting to know if his methods influenced lingual pressures during periods of rest. Proffit and Norton, in this *Report*, postulate that lingual forces at rest are particularly important to occlusion. The point to stress, however, is that studies involving clinical treatments should be done so well that they are not automatically discarded by other scientists when they conflict with data from other research. We hope that the research by Newman and Stansell marks the beginning of a series of studies that will explain the effects of behavioral tongue-thrust treatments.

observed response. Dentists and speech pathologists have identified difficult, important problems concerning swallowing. To date, however, they have accumulated little evidence in support of the behavioral treatments they direct to their tongue-thrust patients. The hypothesis that orofacial pressures interact with other variables to influence occlusion is one that should be compared with evidence and then retained for awhile, rejected, or modified.

Measurement problems will have to be overcome before we can directly test treatments by behavioral analysis or other experimental methods. I'm not very comfortable with a diagnostic procedure that requires the examiner to open the subject's lips in order to glimpse tongue protrusion in midswallow. Even if this measure is reliable and valid, it does not provide us with information about the force and timing of oral pressures at different locations in the mouth. Perhaps researchers studying oral pressures by means of small transducers will provide us with the measure needed for use in treatment studies.

Oral Pressure Studies

Use of transducers to measure lingual pressures on oral structures would appear to provide the means needed to identify phonemena and relationships important in the tongue-thrust area and also to test treatments directed to reduction in lingual pressure. Investigations in this area have involved placement of transducers at different oral sites (McGlone and Proffit, 1967; McGlone, Proffit, and Christiansen, 1967). Acrylic appliances and adhesive have been used to keep the transducers in the desired positions. Experimenters have studied pressures produced at different locations during the production of different phone types by different speakers. Rate of utterance has been tested for influence on lingual pressure, as has phone-type context. Conflicting results have been reported concerning consistency within subjects over repeated measures; however, investigators apparently agree that phone types studied cannot be identified on the basis of distinctive pressure characteristics. Differences among speakers are greater than differences among phone types. Swallow pressures also have been studied. Pressures during swallowing apparently are more variable than pressures during articulation. Finally, we note that Leeper and Noll (1969) have related lingual pressure against the alveolar ridge during syllable production to intraoral air pressure, sound pressure level, and vocal effort. They illustrated these relationships graphically and described them in terms of power functions and exponents. Proffit and Norton review the literature on this topic elsewhere in this *Report*.

Without engineering training or experience with oral pressure instrumentation, it is difficult to assess measurement error as a factor in this kind of work. Proffit, Palmer, and Kydd (1965) mention instrumental baseline shift and cooling effects as sources of error. Calibration data have been reported (Proffit et al., 1966). Workers in this area are disappointed at the failure to find patterns distinctive for different phone types. However, this could simplify the application of these measures to the study of treatments directed to reduction in lingual pressure during different activities.

Oral Pressure Measures in the Evaluation of Tongue-Thrust Treatment

I am not saying that study of oral pressures will provide a quick and easy solution to tongue thrust. Application of oral pressure measures in the study of treatments will be possible only if stable baselines can be established. That is, if variability is great, perhaps in part because of error factors, pre- and post-treatment measures will overlap. Consequently a treatment effect may not be identified even if it actually exists. Some of the studies cited above do not include variability data alongside many of the means they report. Proffit, Chastain, and Norton (1969) conducted a longitudinal study of lingual pressures in children. Some subjects consistently produced higher pressures than others, but within individuals "variation was approximately ±25% of the mean pressure value for any transducer location." I understand the investigators hope to reduce that variability through improvements in their instrumentation.

Before lingual-facial pressures are manipulated in the investigation of a potential clinical treatment, we should be able to identify patients who produce abnormal pressures. If the treatment is directed to occlusion, we must also know something about the characteristics of those pressures and related phenomena that must exist if those pressures are to influence occlusion. In this regard, the distinction between contractile forces and tonic forces may be important (Jacobs, 1969). Contractile forces that occur during speech and swallow involve a small amount of time in comparison with the tonic forces that include the muscle tension at rest that is brought about by the intrinsic elastic properties of muscle tissue. There is little sense in reducing normal pressures or in bringing about pressure reductions too slight or too inconsistent to have the effects desired by the investigator. Certainly, basic information will help the clinical investigator formulate good research questions. If treatment research is directed to a well-defined problem, then success will be shown by a clear solution to that problem. The Salk vaccine, for example, was a successful treatment.

What kinds of evidence will we accept as indicating success in tongue-thrust treatment? According to Perkins (in press) Stansell (1969) found that the oral training by itself influenced occlusion. Should we hold to an occlusion effect as evidence of success or should the criterion be a change in pressure maintained over time and regardless of environment?[6] Probabiy we should study oral training, by itself and in conjunction with orthodontic treatments, in relation to occlusion effects, pressure changes, and speech effects. Undoubtedly, eventually we shall find that a given treatment combination does not have the same effects on all patients. Therefore, we shall have to identify the subject and environmental conditions under which a given treatment can be applied.

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[6] See Wright, Shelton, and Arndt (1969) for a discussion of response automatization with reference to articulation.

RESEARCH DESIGN CONSIDERATIONS WITH REFERENCE TO TONGUE THRUST

Several papers in this *Report* cite a paper by Cleall (1965). I should like to discuss it with reference to designs used in treatment studies. Cleall made a number of measures from cinefluorographic films of subjects in three categories: normal, Class II malocclusion, and tongue thrust. Some of the tongue thrusters were fitted with palatal cribs designed to influence tongue position. Several cinefluorographic films were made of each subject fitted with a crib. The first film preceded placement of the crib. The second film was made six months after placement and immediately before removal of the crib. The third film was made immediately after removal of the crib, and the fourth film was made two months later. Factors other than placement of the crib could account for changes observed between the first and second films. However, the subjects' oral postures in the last two films tended to be similar to those observed in the first film. This return to the original state lends credence to the author's conclusion that the cribs did influence oropharyngeal structure positions. Nevertheless, the article is based on inferential statistics that are not reported, and no control group was used for that portion of the study that involved placement of the cribs. A different design might have helped the author obtain a more satisfactory answer to his question, or to obtain an answer in a more efficient manner. Since Cleall chose to make observations within a single group of subjects, he might have made use of experimental analysis of behavior procedures. EAB investigators would have made more frequent observations of the subjects than were made in this study. Reduction in number of observations at a given filming would have permitted more frequent filming with, perhaps, no more radiation exposure. This would have permitted more thorough study of pretreatment stability and better description of changes made by the subjects. Sequential study of the subjects (Bachrach, 1965, pp. 62-68) might have permitted a solution with study of fewer subjects. It is also possible that treatment variations could have been introduced without greatly increasing the amount of work. For example, subjects could have worn cribs for different periods of time. Cleall's work should spur a number of treatment studies directed to well-stated problems; but with better design and reporting, he could have provided his readers with more answers.

Tongue thrust appears to be a good topic for collaboration between speech and dental specialists in both basic and applied research. Maybe a research program will demonstrate that oral forces responsible for malocclusion are indeed amenable to a few easy lessons, regardless of circumstances. However, other papers in the present *Report* discredit that view.

DEVELOPMENT OF PALATOPHARYNGEAL CLOSURE

Various treatments are used to provide satisfactory palatopharyngeal closure to persons with palate defects. These treatments have been submitted to some testing. I shall review studies pertaining to speech therapy, movement training, or use of speech bulbs as means of developing palatopharyngeal movements. I shall also consider problems involved in the evaluation of treatments directed to modification of closure movements. Surgical treatments will not be reviewed because of space considerations and because they appear to be directed to improvement in function through modification of structure. Generally, palatal surgery is not intended to increase movements but rather to position structures so as to make optimal use of movements already available to the speaker. This is not to say that surgery never results in increased palatopharyngeal movement. Hagerty, Hess, and Mylin (1968) found that their patients made more palatal movements after pharyngoplasty. Apparently their patients did not activate their palates during speech until after pharyngoplasty gave them the potential for closure.

Speech Therapy

In a previous publication, I differentiated between speech therapy directed to improvement in articulation and training directed to increased palatopharyngeal movements (Shelton, 1963). I have also contributed to the viewpoint that the speech clinician should concern himself with speech teaching and not attempt to improve palatopharyngeal closure through training (Shelton, Hahn, and Morris, 1968). Certainly, this clinical position like any other should be submitted to experimental test and should be reevaluated from time to time.

There is not very much evidence concerning the effects on closure of either sound-production-centered therapy or movement-centered training. Nylen (1961) wrote that speech therapy resulted in improved patterns of palatopharyngeal closure. However, he did not describe the therapy. Prins and Bloomer (1965) obtained word intelligibility measures before and after speech therapy administered to 10 subjects with palate problems. They measured palatopharyngeal efficiency on the same schedule by manometric assessment of oral pressure during blowing with nares open and again with nares closed. They also made spectrographic observations. The authors were more interested in assessing the utility of their measures than in evaluation of the therapy provided. Thus, they did not describe the therapy in great detail, and used no control group. However, even though variables in addition to the therapy may have been involved, the results suggest that the therapy contributed to improved intelligibility scores. Inspection of the authors' manometric data indicates that palatopharyngeal valve efficiency was no better after therapy than before. There was a decrease in the frequency with which the oral consonants produced by two subjects were perceived as nasals. Perhaps the subjects improved their intelligibility despite unchanged palatopharyngeal deficiencies.

My associates and I (Chisum et al., 1969; Shelton et al., 1969) provided articulation therapy to subjects thought to have moderate deficiency of palatopharyngeal closure. The subjects improved their articulation, but cinefluorographic measures showed no change in palatopharyngeal closure, in movement of the posterior wall of the pharynx, or in distance between the tongue and either the atlas or the posterior wall of the pharynx. This study certainly does not terminate the need for investigation of the effects of articulation therapy in subjects with cleft palate or palatal insufficiency. The procedure involved study of correlations between counts of activities in therapy and measures of articulation improvement. One try at obtaining data from typescripts of lesson recordings was enough for us. We turned to the use of Sound Production Tasks (Elbert, Shelton, and Arndt, 1967; Shelton, Elbert, and Arndt, 1967; and Wright, Shelton, and Arndt, 1969) to measure articulation change during a period of therapy. We have yet to control the therapy with sufficient precision that we can claim a specific treatment was responsible for a measured response change. We continue to think that under some conditions, articulation therapy or movement training provided to persons with closure problems can result in tongue retraction during speech. This retraction can become highly automatic and is not compatible with articulation of sounds produced with the tongue tip (Brooks, Shelton, and Youngstrom, 1965, 1966).

Additional research is needed to determine under what conditions, if any, sound-centered therapy influences palatopharyngeal closure. This is difficult research because treatments, response measures, and subject variables must be specified with greater precision than has been done in the past. Subjects who meet simple criteria prove to be scarce. I'm not certain that our closure measures are sufficiently precise for definitive studies at this time. However, unless we're prepared to abandon our treatments, I think we have to conduct research in this area. Unless we continue the task, we won't know what technical problems must be overcome to give us a more definitive answer.

Movement Training

Yules and Chase (1969) reported a procedure for developing movements of the pharyngeal walls and incorporating those movements into speech. Basically, movements were elicited by electrical stimulation and then established on a voluntary level through training that used visual cues. A training device was constructed to help the patient establish use of the movements in self-initiated speech. The device provided visual information about acoustical energy detected at the nares and lips. The authors report a reduction in nasal air leakage and elimination of hypernasality.

Once again, the results of research invite further research. We want to know more precisely the relationship between components of the training procedures and specific response measures. Can the gains made be maintained in automatic speech regardless of speaking environment? Are there any negative side effects such as unwanted laryngeal or lingual adjustments? Under what subject and environmental conditions is the training effective?

In our laboratory we have entered into the investigation of these problems. We taught palatal movements to normal subjects in a study of palatal kinesthesis (Shelton et al., in press, a,b). Tash (1970), with the assistance of A. W. Knox and myself, undertook to teach a few normal children and children with poor closure to move their pharyngeal walls as a nonspeech activity and then during phonation of /ɑ/. Training trials were carefully counted by event recorders. Touch stimulation was used initially to elicit responses. To the eye of the examiners, the subjects did learn to produce medial movement of the lateral pharyngeal walls and forward movement of the posterior pharyngeal walls. The study is not complete. Even if our cinefluorographic films show movements of the posterior pharyngeal wall where there was none before treatment—and I don't think they will—we do not expect generalization to self-initiated speech. We are attempting to use sound level and manometric measures as indirect evidence of palatopharyngeal closure. However, we are having some difficulty establishing baseline measures sufficient to support claims for treatment effectiveness.

From study of our own cinefluorographic films, we are of the impression that normal speakers do not move their posterior pharyngeal walls during speech. This is supported by Yules and Chase (1968). However, in the films of some speakers with cleft palates we do see posterior wall movements of considerable magnitude. These movements are often synchronized with movements of the palate. They often occur at times necessary to contribute to speech closure and in locations contributory to closure. They may be in the form of bars or pads, or they may be broader. We should be able to develop these movements through training and to incorporate them into automatic speech.

Massengill et al. (1968) have reported results pertaining to the effects of therapeutic exercise on palatopharyngeal closure. Lubit and Larsen (1969) described an exerciser to be used to improve closure.

Obturator Manipulation

Investigators working with prosthetic speech appliances used with cleft palates often comment that reduction in the size of the bulb may be necessary (Rosen and Bzoch, 1958). For example, Bzoch (1964) wrote, ". . . bulbs which are closely fitted in the nasopharynx at the start may have to be made smaller after a period of time due to the development of increased muscle activity." Several essays pertain to the temporary use of prosthetic devices for diagnostic or training purposes or both (Blakeley, 1960; Curtis and Chierici, 1964; and Alley, 1965). Blakeley (1964) presented three case studies suggesting that repeated small reductions in the size of the speech bulb may result in increase in pharyngeal wall movements. My associates and I (Shelton et al., 1968) described a bulb reduction procedure administered to subjects with open clefts and to other subjects whose palates had been repaired. Subjects underwent as many as three bulb reductions without statistically significant change in articulation scores. Nasal escape of air as measured by use of a water manometer was observed to increase during the course of the study. We're completing our report of the analysis of cinefluorographic films obtained before and after the bulb reduction (Shelton et al., 1970). One subject appeared to produce greater pharyngeal wall movement after reduction than before. We noted that subjects may adapt to bulb reduction in various ways. The subject may learn to displace his appliance with his tongue or he may reduce the space between the bulb and posterior pharyngeal wall by craniocervical posture changes. These changes are different from and much less extensive than those used by McWilliams, Musgrave, and Crozier (1968) for diagnostic purposes.

We are also completing a study wherein four subjects were fitted with speech appliances constructed in such a way that bulbs could be exchanged. Thus a set of bulbs was made for each subject. For a period of time each subject wore a bulb we considered to be optimally fitted. Then each wore smaller bulbs. Each subject was tested repeatedly with his entire series of bulbs as well as with his appliance removed. Dependent variables included oral and nasal sound pressure level, articulation test scores, nasal pressure measured with a water manometer, and measures from cinefluorographic films. Our measures differentiated among the obturation conditions, but my opinion of the data so far as our analysis is complete is that we have no evidence of useful adaptation to the smaller bulbs.

Once again, effective use of a treatment, in this instance speech bulb manipulation, requires study to evaluate specific treatment conditions. Greater thought should also be given to the nature of hoped-for increase in pharyngeal movements. If the bulb serves as an exerciser, is it supposed to increase strength and range of motion, or is it supposed to result in muscle hypertrophy? If the latter, are there unwanted side effects? Perhaps reduction does cause some persons to learn to produce pharyngeal wall movements. If so, what conditions must be present to obtain this effect? Perhaps the period just after the bulb is first fitted is optimal for development of wall movements by bulb reduction. How does the bulb reduction procedure compare with direct training, in effectiveness? Another possibility is that the speech bulb elicits a reflex compensation of the pharyngeal walls and that neither exercise nor training effects are needed (Fletcher, Haskins, and Bosma, 1960). These are interesting problems important to patient management. They are also difficult to answer. What is needed is a highly accurate, quick to use, measure that will provide instant information about palatopharyngeal gap, movement of structures of interest to the investigator, or both. Perhaps the fiber-optic device mentioned by Harris elsewhere in this *Report* will be helpful in this regard. The airflow technology that has been developed also should be tried as an index to closure change in treatment studies.

Velopharyngeal Incompetence and Articulation

Morris (1968, pp. 121-131) reviewed and discussed literature pertaining to the relationship between velopharyngeal incompetence and articulation. Certain concepts in that literature will have to be extended as we work to understand closure requirements for optimal speech improvement with therapy. For example, if closure is more critical for development of good speech than for its maintenance (Isshiki, Honjow, and Morimoto, 1968; Shelton et al., 1968), then perhaps a greater use should be made of speech appliances during the period of speech development. Normal persons have been observed cinefluorographically to produce certain phone types—generally vowels in nasal consonant environments—with some opening of the palatopharyngeal port. Also, persons with defective palates have been observed to speak relatively well. (Readers who encounter such persons are requested to document and report their observations.) I've just cited studies suggesting that persons may improve their speech with therapy even though closure deficits exist and remain unchanged. These observations may encourage us to attempt to develop good speech in persons with closure deficits. However, speech clinicians and their patients have experienced much failure in attempts to do just that. There are statements in the literature, one of which I've cited (Hagerty, Hess, and Mylin, 1968), that indicate provision of good closure through physical treatment is necessary to development of good oral function and speech. I think the goal of surgical and dental treatments in cleft palate should be to provide complete palatopharyngeal closure during the articulation of most phone types. Certainly closure is one variable that will have to be controlled and studied as we attempt to evaluate the behavioral treatments we provide to persons with palate defects. Treatment studies may improve our understanding of relationships we have already studied.

ARTICULATION DISORDERS

In this essay, I've emphasized behavioral treatment of tongue thrust and cleft palate. Each of these phenomena involves articulation. From my viewpoint, the articulation literature should be considered pertinent to understanding speech problems associated with tongue thrust and cleft palate. Subtelny, Mestre, and Subtelny (1964) stated that articulatory phenomena observable by cinefluorography are influenced by phonetic context as well as by skeletodental morphology. Therefore, they say, both sources of variation must be understood before the cinefilms can be interpreted with confidence. I would extend our interest to include additional variables involving normal and disordered articulation.

Articulation errors produced by physically normal persons are termed functional errors. To me, this means that the etiology is unknown; however, as I shall discuss, functional articulation errors commonly are thought to reflect environmental influences on learning.

Winitz (1969, p. 125) has written that "where obvious physical and mental abnormalities are not present, most if not all phonetic errors are the result of incorrectly learned phonemic systems." That is, articulation errors not associated with obvious pathology usually "represent the incorrect learning of the phoneme system of the community language." He cites various kinds of evidence in support of his learning hypothesis. By 2½ years of age, children can produce most of the consonant sounds in their language. Children with poor articulation and children with good articulation have been found to have similar abilities to learn phone types foreign to their native languages. Cross-language comparisons show different error patterns depending on the native language of the speaker. If the etiology were physiological, error differences among speakers of different languages would be fewer. However, Winitz points out that much of our knowledge about articulation disorders is based on correlation and comparison studies. These investigations are important to the formulation of more definitive research, but understanding—and especially the identification of causal relationships—requires longitudinal studies and experiments involving stimulus-response manipulations.

I'm tempted to apply Winitz' term of criticism, *traditional,* to his own hypothesis. There is certainly a tradition in speech pathology to attempt to explain etiology in learning terms when no physiological deficits can be found. Perkins and Curlee (1969) have described the flaws in our use of a causal pecking order. As they point out, psychogenic factors operate even when physiogenic defects are present. The speaker who has a cleft palate learns his speech just as the normal person learns his. Definition of functional disorders through exclusion of physiological defects is a fault. Winitz, however, uses this distinction only to focus on subjects of interest to him; that is, persons free of obvious organic disorders. He emphasizes the need for investigations involving such subjects.

Persons with oral pathology are subject to functional errors as well as to errors directly attributable to their oral pathology. Van Demark and Van Demark (1967) found that for many articulation error categories, speakers who had cleft palates but normal breath-pressure ratios were indistinguishable from persons of comparable age who had functional articulation disorders. This suggests the possibility of a common etiology.

Pitzner and Morris (1966; Morris, 1968, pp. 142-147; Carpenter and Morris, 1968) hypothesized that articulation errors resulting from deficiency in palatopharyngeal closure sometimes give a child feelings of speech inadequacy. This, in turn, results in less of "the usual trial and error procedure of learning speech which results for normal children in better approximation of speech sounds." Thus the physiological deficit influences experience which, in turn, retards the learning of sounds not directly dependent upon palatopharyngeal closure.

In my opinion, treatment studies involving persons with functional articulation disorders will contribute to our understanding of speech produced by the person with an oral-facial disability. (See the chapter by Noll in the present *Report.*)

OTHER DISORDERS

Space does not permit me to discuss a number of applied problems pertinent to dentistry and speech. Relationships between maxillary arch measurement and articulation in cleft palate should be studied. The relationship between occlusion and articulation is of interest even in the absence of unwanted tongue and circumoral muscle movements.

Bzoch (1965) and Phillips and Harrison (1969) have presented data regarding the articulation development of preschool children with cleft palates, and argue for early speech therapy. I would prefer to avoid giving therapy to children who have a good chance of overcoming their speech disorders without remediation. However, failure to correct the speech disorders early may result in various complications. As Winitz (1969, p. 216) points out, we need to determine whether articulation errors interfere with children's learning of reading and spelling skills. If they do, then it is especially important that the articulation errors be corrected as early as possible. This gets us into the problem of the nature of articulation errors that are associated with retarded school achievement, poor personal adjustment, or other problems.

There are many applied phenomena with which we must be concerned. In our various laboratories, we must take on different problems so that our efforts are supplementary. However, we must also engage in enough replication work that we can establish the generality of our results. We've seen work of this kind in the studies of the relationship between palatopharyngeal variables and articulation.

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PSYCHOSOCIAL DEVELOPMENT AND MODIFICATION

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A review of the literature relating to the psychosocial status of patients with maxillofacial deformities, both congenital and acquired, leaves one with the distinct impression that the clinician might wisely question much that has been written. The researcher, on the other hand, will quickly realize that information on the psychosocial dynamics of the dentofacial complex is often scanty, unsophisticated, misleading, restricted, and inadequate for clinical application. This general evaluation of the situation is compatible with the findings of Matthews and Ohsberg (1966) who surveyed the cleft palate literature in this area for the years 1940 through 1965 and with those of Ruess (1967). This present confusion is not necessarily the result of poor research. Many excellent studies have been carried out, and they will serve as lodestars for future investigators. The real problem lies in the fact that, in spite of a vast literature on relatively narrow aspects of many interrelated fields, definitive knowledge about personality in general remains primitive and highly speculative. Logic, empirical evidence, and clinical experience often tend to endow essentially unproven theories with the status of "proven fact" that only the most ill-informed or unorthodox would presume to question.

Investigations designed to learn how a maxillofacial deformity influences the person who has it are almost bound to fail if one has the courage to admit at the outset that it would be difficult to explain the psychodynamics of that same individual if he did not have a maxillofacial defect. This leads to the recognition that it is not maxillofacial disfigurement that is the source of research concern. Research concern lies with people, all kinds of human beings from all kinds of backgrounds, whose only reason for being grouped together is that they have cleft palates, facial scars, missing ears, surgically excised mandibles, drooping eyelids, humped noses, receding mandibles, or any one of a dozen other deformities. Their common facial tragedy invites the study of certain aspects of their behavior because it is assumed in our culture that, if people are not beautiful, they must be unattractive in other aspects of their development as well. The literature is full of value judgments to this effect. A few, beginning with Brophy in 1909 and ending with Johnson in 1967, serve as examples:

> The child's embarrassment in the knowledge that he is deformed drives him, usually, into isolation. He refuses to associate with his fellows and his unfortunate condition prevents him from enjoying the companionship of others. (Brophy, 1909)
>
> Physical deformities play a potent role in pathogenesis of the mental syndrome. (Sperber, 1930)
>
> . . . facial and oral deformities . . . may have grave psychological effects. (Olinger, Singer, and Katz, 1941)
>
> The cleft-palate child is an oral and facial cripple who often tends to react to mundane conditions in a manner similar to that of other types of cripples. (Beder, 1946)
>
> When speech develops abnormally due to a mechanical difficulty . . . the resulting psychologic effects are usually profound. (Easley, 1960)
>
> Many children with cleft palate, especially if the lip is also involved, are self-conscious about their appearance. They are even more self-conscious about their speech impairments and are often shy and tend to avoid talking. (Johnson and Moeller, 1967)

Similar statements are liberally scattered throughout the literature (Baker, 1949;[1] Cooper et al., 1960; Easson, 1966; Epsteen, 1965; Ricketts, 1956). While they may be true, and certainly appeared to be to the writers who were also observers, they are not objectively supported; and it remains impossible to assess personality from physiognomy.

SOCIAL ATTITUDES

It is possible, however, that these expressed attitudes on the part of professional people may mirror the attitudes of the world at large. Schwartz and Landwirth (1968), again without real evidence, conclude that "the belief that a warped body means a warped mind is deeply rooted in the public unconscious." This general opinion is shared by Perrin (1921) and Kahn (1956). Perrin commented, "The statement that people do react definitely to the physical in other people may be made safely without statistical evidence." This conclusion would infrequently be challenged today. The literature offers adequate evidence that many writers agree with him—even though Perrin himself found from his own investigations that physical attractiveness is to be explained primarily in terms of behavior!

MacGregor and colleagues (1951, 1953), with somewhat more supportive information, believe that, in this society, facial deformity is considered to be a handicap because we are prejudiced against and generally disapproving of such disfigurement. Overt and covert superstition and suspicion exist even among professional people, and there is frequent reversion to stereotyping. The association of a high forehead with intellectual prowess, a low forehead with mental deficiency, a receding mandible with weak character, and a pointed nose with reprehensible curiosity are examples of this behavior. To test the accuracy of their assumption, these authors showed a photograph of a facially disfigured

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[1] Baker, H. K., The rehabilitation of the person with cleft lip and cleft palate. American Medical Association Scientific Exhibit, Atlantic City, New Jersey (1949).

man with both high intelligence and high achievement to 60 judges. All but one evaluated him in negative terms as a person, and 30 thought he must be mentally retarded. Cook (1939) had 10 expert judges attempt to judge intelligence from 150 photographs. The experts not only failed; they couldn't agree among themselves. Thornton (1943) went so far as to show that judges respond differently to two photographs of the same individual when the pictures differ in just one dimension. For example, the smiling picture was rated higher in sense of humor, kindliness, and honesty than was the sober picture. The addition of glasses led to higher ratings of intelligence, dependability, industriousness, and honesty. Bakes (1952) may have been right when he suggested that the people around him will determine whether the child with a cleft (or other facial disturbances) evaluates it as a handicap or as a difference.

It seems probable that the facial cripple lives with social pressures that society has minimized and denied in much the same way it has ignored the uncomfortable plight of the black man. Barker (1948) first suggested the resemblance of the disabled to minority groups. Cowen, Underberg, and Verrillo (1958) demonstrated the similarity when they compared attitudes toward the blind with attitudes toward minorities. An adverse environment which helps to shape the behavior of the handicapped person and his family may be created by a society which then reacts negatively to the product of its creation, accusing him of being unable to test reality when he senses and responds to "real" social disapproval. Indeed, "reality principle" is considered by Grayson (1951) to be fundamental in physical rehabilitation. Coffman (1963) has referred to reality for people with "abominations of the body" as a form of stigma and notes our belief to the effect that "the person with a stigma is not quite human." This whole area of the unique social milieu of the disfigured person is one that demands thoughtful and creative attention—particularly if we agree with Levy (1932) that "children find out about their own body by the talk and observation of others," and if we harken to Erikson's (1950) wisdom when he says:

> We suggest that, to understand either childhood or society we must expand our scope to include the study of the way in which societies lighten the inescapable conflicts of childhood with a promise of some security, identity, and integrity. In thus reinforcing the values of the ego, societies create the only condition under which human growth is possible.

PARENT ATTITUDES

The baby with congenital malformation of the face is born to parents who are a small segment of what may eventually reveal itself to be a hostile society. They have perhaps anticipated the birth of a "perfect" baby, while, at the same time, they may have nurtured ill-defined fears of "something being wrong." When something is indeed wrong and it is wrong with the face, to which Linn (1955) has referred as the "oldest element in the body image," there is bound to be reaction of some sort on the part of the parents. It is difficult to imagine that this response could be either positive or neutral. We assume, therefore, that it normally is fundamentally negative. Green (1965) referred to this as a "family crisis." Precisely what the response will be will depend upon the people who are the parents, how much of a threat a congenital anomaly in their baby is to their own egos, and their use of psychological defense mechanisms. These parental dimensions are probably of far greater importance to the facially deformed infant than is the so-called "impact" of the deformity. These vast individual differences may explain why most specific attempts at measurement of influence have lead to confusion and, perhaps, to unwarranted accusations directed to parents. However, we cannot ignore the clinical experience which led Solnit (1961) and Tisza and Gumpertz (1962) to conclude that the parents of a defective child must work through a mourning experience before they are able to deal with their living child's problems and accept him without negative feelings. The implication here is that the birth of a defective child is a painful experience for parents and that their feelings, negative though they may be, are normal feelings.

Many writers have made reference to these negative reactions (Kinnis, 1954; Lillywhite, 1957, 1958; MacCollum and Richardson, 1954; McDonald, 1954, 1956, 1959; Sleeter, 1965; Spriestersbach, 1961b; Thurston, 1959; Wishik, 1951). On the other hand, there have been relatively few systematic investigations of these observations and almost no effort has been made to understand the difference between a normal response pattern and a pathological one. Norval, Larson, and Parshall (1964) studied 51 low- and high-stress families in an investigation of indigent mothers of babies with cleft lip and palate. While there were no statistically significant differences between families, trends suggested that the emotional trauma may be greater for younger than for older parents and for families with fewer children. The type of cleft would also seem to be a factor in stress. None of the "lip-only" babies were in the high-stress group, but the authors attested to a limited population. However, this finding is borne out by Spriestersbach (1961a). Clifford (1969a) has contributed recent information on this subject. He studied 60 pairs of parents whose children with cleft palate had not passed their second birthdays. They each completed a self-administered questionnaire and rating form providing information in four major areas. No control group was used. His findings suggest that parents rate a cleft lip and palate as a more severe problem than they do a cleft of either the lip or palate. Parents also see the baby with a cleft lip and palate as being more "irritable-active" than is the case for less extensive disfigurement, and they feel that the more severe problems have greater emotional impact in their lives. Mothers are more affected by the handicap than are fathers, but neither mothers nor fathers view the cleft as playing a major role in marital adjustment. Clifford interprets his data to imply that parents are truly more reality oriented than had been thought previously, since the severity of the symptoms seems to play such a major part in the response of the parents. Slutsky (1969) reports similar findings. Further insight into parental feelings may bear out these results without necessarily disproving the view that a facially disfigured baby is a source of grief and anxiety to mothers and fathers. Perhaps being reality oriented is also to hurt.

It is clear that the literature on the actual initial impact of anomalous conditions in children leaves many questions unanswered. Retrospective investigations of this type are often disappointing because of meager information about attitudinal evolution. Our psychiatric colleagues would probably be justifiably suspicious of the parent who seemed to imply that "it didn't matter at all; he's just like everyone else," even as they would be concerned about the inability to see any positive values in the child with a malformed body. The strength and health of the psychological control mechanisms available to the parents will eventually have to be evaluated. Perhaps the best place to begin such investigation is in the delivery room or as close to the moment of "assault" as possible, before time has had an opportunity to work its sly psychic tricks.

In spite of limited knowledge about parents of children with facial handicaps we continue to believe clinically that their basic attitudes, regardless of origin, have relevance to the developing child with or without disfigurement (McWilliams, 1956). Backus et al. (1943) suggest that it is usually safe to say that "when parents are well adjusted to having a child who has a cleft palate, the child himself will be adjusted and happy." Alpert (1959) views the problem as considerably more complex than that. In reporting a treatment experience with Kevin, he considered "birth defect and surgery" to be what "Phyllis Greenacre calls the 'organizing experience' of Kevin's life." However, he also viewed the early feeding problems and the frustrating mothering role as important factors in Kevin's troubles. MacGregor et al. (1953) concluded from their detailed study that "the single most important factor in the genesis of maladjustment in cases of facial deformity in childhood is parental behavior influenced by "other life aspects." Watson and Johnson (1958) concurred in this conclusion when they found from intensive psychotherapy that the child perceives and imitates parental attitudes toward his body and its parts and that the child also perceives and imitates the defenses against anxiety utilized by the parents. We wonder how this conclusion differs from our philosophies of childhood in general from as far back in time as the Old Testament (Exod. 34:7; Deut. 5:9; Prov. 22:6).

The recognition of the vital role of the parents, particularly in cleft palate, has led to the publication of many written materials designed to help them. These have been summarized and evaluated by Wylie and McWilliams (1965, 1966). Their conclusion was that such materials are rarely ideal and that the general nature of the publications precludes their specific application to a particular case. However, Carr's (1959) idea that "efforts to broaden (parents') knowledge and understanding will do much to create a good life for their children" persists. Certainly, misunderstanding the nature of the problem may have profound negative influences in a child's life (Shannon, 1955). Bradley (1960) has shown that parents themselves want help with their questions, preferably from appropriate specialists, and that they prefer to have information provided in the first year of the child's life. Lowe (1961) also reported evidence from a survey of 80 parents that they want aid. Spriestersbach (1961a) and Hill (1956) believe that the adequacy of the information the parents have will determine in part the ultimate adjustment of the child. Yet Spriestersbach found the parents of children with cleft lips and palates to be poorly informed even after counseling. Confusion and anxiety may coexist, and this could and should be explored.

Goodstein (1960a, b) studied 170 mothers and 157 fathers of children with cleft palates by means of the MMPI, and compared their responses to those of 100 control parents of normal children. The former were somewhat more anxious than were the parents of normal children. Also, of possible significance in future research, the parents of older children with cleft palates seemed to be more poorly adjusted than were the parents of younger children. It is possible that peer relationships for older children grow more complicated and that the parents realize to their own peril that their children's problems are actually greater than they had thought. Goodstein did not relate parental anxiety to understanding or insight or to the clinical pictures of the children.

This brief review of the current status of knowledge about the parents of children with clefts should be sufficient to demonstrate that efforts to understand their problems have been somewhat naive. There has been a tendency to forget or to ignore the dynamics of the parents as people operating within a social structure and with historic roots which predate the birth of a defective child but which continue as vital sources of nurture—or of emotional malnutrition—to the ends of their lives. To expect that disfigured offspring will be accepted and assimilated into their lives according to a measurable and predictable response scheme is probably not realistic. So far as parents are concerned, they must be viewed as people with common uncommon problems in a sometimes hostile and repressive environment. In short, the facial disfigurement becomes a condition of stress with which they must deal as effectively or ineffectively as they handle stress in general and this problem in particular.

PATIENT ATTITUDES

Wylie and McWilliams (1966) found that, of 27 publications written for parents of cleft-palate children, 12 discussed parental emotional responses. Only three appeared to be concerned about the child who would live with the anomaly, endure multiple surgical insults, be subjected to countless oral examinations (often conducted by the sacred team descending upon him in a horde), have his ears checked repeatedly for the probable necessity of myringotomy, talk so that the "experts" can assess his verbal output, reveal the secrets of his mental and psychosocial development, and wear dental appliances—all to the end of making him a more acceptable person. He might also have to listen to hundreds of comments over the years about the adequacy of his habilitation, the elevation of his nostril, the prominence of his lip scar, the intelligibility of his speech, how he fits into his peer groups, and what he is doing academically. Clinically, one sometimes wonders how it must feel to be the walking summation of all those parts. Can all this reasonably result in a sturdy, invulnerable "self"? Are we really so far off base when we wonder about the adjustment of such a child?

Body Image

Bettelheim (1950) points out that "in psychoanalytic theory, the body image is the basis for the formation of the ego. If this is so, one can easily understand why a poorly functioning body may lead to a weak ego." Schilder (1950) noted Freud's recognition of our interest "in the integrity of our own body" and pointed to the importance of body openings. He suggested that "a nucleus of the body image is present in the oral zone from the beginning." His patient A. M. considered himself ugly and unacceptable. He experienced no change in attitude following work on his nose. Schilder concluded that "our own body is an image and is built up in ourselves in accordance with our instinctive attitudes. An actual change in the appearance can therefore only have a limited result." Concern with body image is apparent in the literature, but methods of evaluating it have been disappointing.

Cath (1957), in a study of patients with respiratory poliomyelitis, an acquired as opposed to a congenital defect and one of far-reaching consequences, concluded:

> In every type of physical handicap, there exist for the disabled person the problems of dealing with the trauma, the need to deny, the regression and the depression which are so characteristically observed. Later, a patient must come to terms with the discrepancy between his body-image and his body-structure.

Springer (1963), as might be expected, found greater distortion of body image reflected in drawings of traumatic amputees than in those of congenital amputees.

Researchers have often felt that studies of body image viewed from human figure drawings might reveal the concerns of patients with facial disfigurement. This has, in general, been a relatively fruitless effort, perhaps because the designs of the studies have yielded only meager information or because methods of procedure are still crude. Palmer and Adams (1962), using the Draw-a-Person test and the drawing of the full face by ten children with clefts of the lip and palate and two control groups, did not find measurable differences in the products of the groups. Corah and Corah (1963), in their study of 12 children with cleft lip and palate and 12 without, also found little evidence to support the contention that physical handicaps will be directly represented in figure drawings. The drawings did, however, reflect an overall poor quality suggesting a probable distortion in body image. When the authors derived discrepancy scores based on differences between Binet and Goodenough mental ages, the children with clefts showed significantly greater differences than did their controls, again indicating some possible distortion in body image—if, indeed, the drawings can be assumed to reflect such imagery.

Abel (1953) studied, also through human figure drawings, 74 patients with facial disfigurement which they all considered to be handicapping. Of interest here is the fact that some subjects rejected the task completely. However, it was possible to compare the drawings of 26 mildly disfigured with those of 19 severely disfigured people. Twenty-one of the mildly disfigured, while they stressed their disfigurement verbally, showed no drawing distortion. Eleven of the 19 severely involved did show some type of body image distortion, but eight showed none at all. These findings, along with others (Blair, 1936; Knorr, Edgerton, and Hooper, 1968; Van Duyn, 1965), suggest the need to understand the exaggerated feelings of many mildly disfigured people as well as the reality-based behavior of some severely marred individuals. How are people with facial disfigurement supposed to feel? Are we able at this time to recognize "normal" responses when we meet them? Probably not. Future research should be addressed to these questions.

Integration of the feeble information now available on body-image disturbance certainly would indicate the need to consider congenital versus acquired problems and to recognize the importance of viewing body image as a function of total life experience rather than as a reflection of a single factor such as facial disfigurement, however dramatic and all-encompassing it may be. Fischer and Cleveland (1965) express their approval of the "sharpened realization that body attitudes are often the result and reflection of interpersonal relationships. One finds fewer instances in which studies tacitly accept that body attitudes pertain simply to the literal physical characteristics of the body." Perhaps so, but this aspect of our knowledge is still woefully lacking in the dynamic multidimensional investigations that seem indicated. In addition, as Barker et al. (1953) so logically state:

> Almost all these studies find severe social maladjustment to be associated with severe cosmetic defect. However, the sources of almost all the subjects are medical and psychological clinics. This means that disturbed subjects have been selected in advance, in some degree. It is not known how typical they may be of the whole disfigured population.

Some congenital facial deformities dictate the necessity for one or more surgical procedures at what are believed to be crucial ages in psychosexual development. Indeed, some writers are persuaded that operations in childhood invariably have important psychological sequelae (Pearson, 1941). Anna Freud (1952) has said that, in the analysis of adult patients who have had operations in childhood,

> . . . the surgical attack on the patient's body acts like a seduction to passivity to which the child either submits with disastrous results for his masculinity or against which he has to build up permanent pathologically strong defenses.

Of further concern here is Anna Freud's contention that the meaning of surgery in a child's life "does not depend on the type or the seriousness of the operation . . . but on the type and depth of the fantasies aroused by it."

We know next to nothing about the role of body image in the acceptance and course of surgery, and we certainly are almost completely uninformed about the psychic sequelae of surgery for different people at varying ages, although Irving Janis (1958) has made a noteworthy contribution in his *Psychological Stress*. To attempt to study this problem in a particular population such as clefts of the palate, orbital cephalocele, cherubism, double lip, hemifacial microsomia, or severe facial scarring is to ignore once again the interrelationships which must logically exist among complex human dynamics of which facial disfigurement, congenital or acquired, is only a part. It is apparent that new methodologies are essential if we are to correct the errors of the past.

Psychological Characteristics

As Ruess (1965) noted, there are still few systematic studies of the psychological characteristics of persons with cleft palate, and, it should be added, of persons with other kinds of facial disfigurement. However, some investigators have attempted to get at the attitudes and problems of such individuals. The bulk of the work appears to be in the area of cleft palate. These studies may serve to direct our attention to procedures and findings that have relevance to facial disfigurement in general.

One of the earliest carefully designed investigations was carried out by Sidney and Matthews (1956). They compared 21 children with cleft palate with two matched control groups on a sociometric questionnaire, the California Personality Test, TAT, Teacher's Rating Scale, and the Vineland. Their data did not lend support to the assumption that children with cleft palate suffer from poor social adjustment. This confirms earlier but less well-defined conclusions reached by Walnut (1954) and, later, by Watson (1964). Hackbush (1951) published conclusions but no data to the effect that there probably is "no such entity as a cleft palate personality" although her projective test results pointed to "limited personalities with little emotional contact."

Clifford (1967) studied 20 children with cleft lip and palate, using the semantic differential technique. These children rated cleft palate slightly more favorably than cleft lip, but rated both of these conditions more favorably than asthma, amputation, and cripple. Mouth, nose, and face had less positive value than more distal body parts; and, surprisingly, they evaluated the cleft condition as a mild illness in the severity range of headache. This study, however, does not really tap the children's feelings about having this comparatively mild disorder. It is one thing to understand a problem on an intellectual level and quite another to accept it emotionally. In short, clinical experience indicates that the ability to verbalize that "other people are worse off than I am" may represent a valiant effort on the part of the patient to make that attitude his own and thus live more comfortably with things that distress him. Clifford (1969b) later reported that children with cleft lip and palate and asthmatic children both rated themselves positively on self-concept measures but that the lip-palate children perceived themselves as less well accepted at birth by their parents. Spriestersbach (1961b) reported that his cleft-palate children voluntarily recited in school, felt that they did things easily, but liked other children less frequently than did their controls. In addition, the children with cleft palate reported less teasing at home than did their peers. Their mothers appeared to be somewhat reluctant to describe them in negative terms. If these latter two findings are accurate, children with cleft lip or palate, as was suggested earlier, may encounter the prejudicial behavior which has to be endured by other minority groups.

Tisza et al. (1958) found that the preschool cleft-palate children they observed psychiatrically seemed to show "unusual self-sufficiency, postural tension, muscular rigidity, and orientation to activity." They avoided interpretation of their results because they felt their material was too limited. However, Tisza, Irwin, and Zabarenko (1969) later evaluated the dramatic play of 11 preschool children with cleft palate and concluded that these youngsters expressed fantasies of unusual depth and intensity involving oral aggression and incorporation. In addition, they feared maternal rejection and realized that even submission to surgery did not guarantee acceptance. While these children seemed to suffer conflict between active-aggressive and passive wishes, Tisza also stressed their ego-strength as demonstrated by their ability to act out painful experiences and then cross the bridge back to reality.

It is the experience of many clinicians that children with clefts are rarely presented to child guidance centers for psychiatric care, and Birch (1952) did not find a single child with cleft lip or palate among the 600 most severely disturbed children in the Pittsburgh Public schools. Demb and Ruess (1967) found that the high school dropout rate for 64 cleft-palate patients was 25%, while it was 42% for their sibling group. The cleft-palate subjects did better in this regard than did their siblings. In an effort to evaluate the effects of cleft palate upon social development, Goodstein (1961) scored the Vineland Social Maturity Scale for 139 children with cleft palates and 174 normal children, from interviews with their mothers. Cleft-palate children under 5 were 11.8 social quotient points below their controls, while children aged 5 through 16 were only 3.7 social quotient points below their controls. The author concluded that these children need not be considered "crippled." Watson (1964) could find no differences between boys with and boys without cleft lips and palates aged 8 through 14 on the Rogers Personality Inventory. These combined observations tempt one to support an interpretation of the literature compatible with that of Goodstein (Spriestersbach and Sherman, 1968) when he said about adults with cleft palate:

> Indeed the informal observational impression suggests that the typical adult with cleft palate is happily married, gainfully employed, and a generally useful, contributing member of society.

Further consideration of this matter, however, suggests that that conclusion may be premature. Gluck et al. (1965) reported that 50 cleft-palate children were more frequently shy and enuretic than were children typically seen in a child guidance center but that they were less often reported to have the disruptive behavior patterns which lead parents to seek psychiatric help for their children. What this means is not clear, in view of the later findings of McWilliams and Musgrave (1966) to the effect that cleft-palate children with normal speech have significantly fewer behavior disturbances than have cleft-palate children who speak poorly in the presence of adequate mechanisms.

Bad temper and enuresis are typical of the latter group, with bad temper predicting the presence of a significant number of other behavior problems. It may be that the "shy" cleft child is indeed aggressive with extra-punitive needs (English, 1961) under certain circumstances. It would be wise to refine and define subject selection so that meaningful information can be derived. Until this is done, we should perhaps exercise extreme caution in drawing conclusions about the emotional state of children with clefts and other maxillofacial disfigurements.

A bit of additional light is shed upon this situation by a small group of informal studies from surgical-psychiatric teams of researchers. As early as 1939, Baker and Smith studied 12 patients with long-standing facial disfigurement. About one-third of this group were classified as having moderately adequate life adjustments. Another third were described as having recessive or inadequate personalities with tendencies to retreat behind the handicap and unconsciously use it as a defense. The remaining third were considered to be prepsychotic and psychotic persons for whom the facial abnormality was the focal point of the schizophrenic process. Their findings suggested the desirability of having psychiatric assistance for certain surgical patients.

In 1934, Updegraff and Menninger, on the basis of experience, felt that the motivation for seeking a surgical solution to severe facial deformity was so obvious that it might be assumed to be entirely rational and conscious. Their concern lay with the patient who sought surgery for vague, unconvincing, or inadequate reasons. In these cases, a decision must be made concerning surgery's ability to meet psychological as well as physical needs. They reflected upon the possibility that surgery may have a psychic therapeutic value when guilt-ridden patients subconsciously assess the procedure as a deserved punishment.

Peck (1948) reported the results of a 10-year uncontrolled experience involving 663 plastic procedures on 376 men in the Illinois State Penitentiary. While his conclusions are observational in nature, they do suggest some possible research directions. He felt that physical aberrations are not usually the dominant cause of criminal careers but that improving physical status results in improved peer and family relationships. In the case of young delinquents, disfigurement which leads to name calling—"monkey face," "dog ears," "fish face"—may have "trigger value" in the development of adult criminals. A humorous and perhaps questionable suspected outcome for a few subjects labeled as probably confirmed antisocials was that many were doing well on the outside. Others, with their improved appearance, had given up petty crime and had "risen to higher and more subtle anti-social efforts."

Updegraff and Menninger (1934), from their clinical observations alone, believed that the nose, occupying so prominent a position in facial physiognomy, was most frequently selected by patients as the focal point of dissatisfaction. Linn and Goldman (1949) later psychiatrically evaluated 58 rhinoplasty patients and concluded that, as a group, they were mentally ill. While they referred to the "rhinoplasty syndrome," they believed that surgical improvement of the nose was not hazardous to these patients psychologically, that it was often helpful, but that surgery would usually have to be combined with psychiatric treatment designed to help such individuals "reorganize their personalities."

MacGregor and Schaffner (1950) conducted sociological interviews with 73 potential rhinoplasty patients in the age span when physical attractiveness is assumed to be important. Fifty-nine of their subjects were unmarried, and there was almost always a psychologically based "wish for change." We might add, parenthetically, that this finding is hardly surprising! However, these authors were more cautious than Linn and Goldman (1949) and felt that rhinoplasty might be contraindicated if the patient presented confused reasons for wanting surgery or over-emphasized a minor defect.

Edgerton and his associates (1960) report similar findings in their psychiatric study of 98 patients with minimal deformities. Rhinoplasty was the most frequently requested procedure, and 70% of the sample were assessed as having a psychiatric disturbance. Half of the mentally distressed patients fell into the category of "personality trait disorder–schizoid or obsessive-compulsive personality." These authors fairly state:

> It is clear that the criteria for such a diagnosis are arbitrary and the vast majority of people so diagnosed would, at most, come to non-psychiatric attention as shy, rigid, timid, and so forth.

Their evaluation of the effects of surgical treatment for these patients led them to the conclusion that the assignment of a psychiatric diagnosis could not be used in deciding for or against surgery. Forty-eight patients were reevaluated six months postoperatively. Forty-six of these were considered surgical successes, and 45 expressed pleasure with the results.

Jacobson et al. (1960), utilizing both the psychiatric interview technique and a group of projective tests, studied 20 male patients seeking cosmetic surgery for defects that were not the result of trauma or major congenital malformation. Rhinoplasty, again, was the most frequently requested procedure. Over half of the men were between 20 and 40 years of age and were single. The authors judged these men to have "serious emotional illness" involving a conflict between cultural background and current cultural circumstances, challenges to masculine effectiveness, difficulties with heterosexual adjustments, difficulty in identification with their fathers, and intensely ambivalent relations with their mothers. "The male cosmetic patient's personality problems are sweeping rather than limited." This is in contrast to the findings of Edgerton, Jacobson, and Meyer (1960) and Jacobson, Edgerton, Meyer, and Cantor (1961) to the effect that women seeking rhinoplasty gave less evidence of psychopathology than any other classification of plastic-surgery patient.

This particular group of studies led Jacobson, Meyer, and Edgerton (1961) to join Berndorfer (1949) in his plea for recognition of psychic phenomena in the clinical management of patients with facial problems. Knorr, Edgerton, and Hooper (1967), a part of the same Hopkins group, later strengthened this conclusion by the results of a survey of 692 plastic surgeons relative to their experience with the so-called "insatiable" cosmetic surgery patient. Only 13% of the surgeons indicated their unequivocal willingness to treat such patients. Only 7% felt certain that benefits were to be derived from surgery, and only 7% felt that this type of patient stops seeking surgery. The surgeons' reactions to these patients ranged from sympathy and pity to hostility and rejection, as demonstrated by the comment, "They give me the creeps." The authors equate this type of person with the ambulatory schizophrenic and suggest that his active seeking for surgical answers to his problem may abate in the late thirties with the "burning out" process associated with his mental illness. The necessity for psychiatric involvement is again stressed.

Gustave Aufricht's (1957) opinion is that "when a plastic surgeon accepts a patient for cosmetic operation, he is undertaking one of the most responsible tasks in plastic surgery." Few would disagree with his point of view, but the present state of the overall literature is not likely to ease the surgeon's burden.

Are people with facial disfigurement poorly adjusted? Some are, and some are not. Can the disturbed group be selected on the basis of pathology alone? Certainly not, but the clinician probably has some right at this point to be wary of the anxious patient with a mild deficit, particularly if it is a man who is dissatisfied with his nose. On the other hand, we must be aware of the methodological limitations that make the assessment of personality in objective terms a frustrating experience for the researcher. There is considerable evidence in the body of literature reviewed here suggesting that clinical observation and psychiatric appraisal of patients with facial deformities or disfigurement lead to the tentative conclusion that psychic distress to one degree or another is an almost invariable associated problem. At the very least, the patient shares the common, human necessity for coming to terms with himself. The dilemma lies in the fact that controlled procedures designed to help these patients express their anxieties and aberrant attitudes have not lent support to the "feelings" of the clinician. We must not ignore the feelings, even though we must question them. It could well be that our measuring instruments are inappropriate to the task. Indeed, we may be guilty of a simplistic attack upon a many-faceted problem. The analyst may hold the master key after all.

LANGUAGE DEVELOPMENT

Discussions of language development are not usually incorporated into work on psychosocial matters. However, there is an emerging body of information in this area which seems to relate at least partially to psychosocial dynamics and which cannot reasonably be omitted. Language problems have been most systematically studied in relationship to cleft palate, probably because of the high incidence of speech disorders necessitating clinical intervention. The terms *speech* and *language* as used in this paper have reference to specific aspects of human behavior. *Language* is to be interpreted as a symbolic system which encompasses all aspects of communication, both expressive and receptive. Speech is the oral expression of those symbols.

Spriestersbach, Darley, and Morris (1958) found that 40 cleft-palate children from three to eight years old had a reduction in mean sentence length and were retarded in verbal output and vocabulary usage in comparison with their controls. However, recognition vocabularies were superior; and structural complexity was not different from that of the normative group. Bzoch (1959) observed that more than 50% of the children he studied had delayed speech development. Morris (1962) reported that his 107 children with cleft lips and palates, and ranging in age from 2 to 15, were less adequate than their controls on the Ammons Picture Vocabulary Test, vocabulary subtest of the Wechsler Intelligence Scale for Children, mean sentence length, complexity of structure, variety of words, and articulation skills. Smith and McWilliams (1966) speculated that the image of defectiveness in verbal output might restrict verbal productivity. However, their 22 10- and 11-year-old children with cleft palates were reduced on measures of creativity even when speech adequacy was not a factor and intelligence was held constant. The authors wondered if inadequate self-concept associated with possible shyness, dependency, rigidity, strong emotional ties to parents, and safe, predictable, nonthreatening habits of response might account for the reduction in creative abilities—even though these presumed attributes could not be proved.

While the foregoing study was in progress, Shames, Rubin, and Kramer (1966) were developing new tools for evaluating overall language. Their tentative results suggest that cleft-palate children lag significantly in most aspects of verbal functioning in the preschool years but that these deficiences may not be constant or predictable from one age level to another.

Smith and McWilliams (1968a, b) continued the language studies by administering the Illinois Test of Psycholinguistic Abilities to 136 children, aged 3 to 8 years, 11 months, with cleft lip and palate. The children revealed general language depression with particular weaknesses in vocal expression, gestural output, and visual memory. Unlike the report of Shames, Rubin, and Kramer (1966), there was a tendency for the deficits to increase with age. As a follow-up to these studies, Ebert (1968) utilized Myklebust's test of written language skills and found no differences between cleft-palate children and their matched controls.

It is of interest to note here that Tisza et al. (1958), in an often overlooked portion of their study, administered the Bender-Gestalt to 11 of their cleft-palate subjects and were impressed with the children's perceptual errors in the "structuralization" of certain motor gestalten. "These involved primarily the failure to maintain the correct proportions throughout the drawings and the inability to reproduce the proper spatial relationships of the tangential and overlapping designs." This whole area of visual perception and its relation to language, personality, and environment obviously warrants greater study.

In a more recent investigation, Philips and Harrison (1969) compared 137 cleft-palate children 18 to 72 months of age with 165 children of similar age but without cleft palate. A number of test and observational techniques were used. The cleft-palate children were inferior to their controls on the Peabody

Picture Vocabulary Test and a Language Ability Test. The cleft-palate children only were also evaluated using the Mecham Verbal Language Scale, and they showed language ages lower than their chronological ages. An attempt was made to compare the least retarded cleft-palate children with the most retarded on a number of variables that might help to explain the language retardation. However, none of the variables studied shed light on the roots of the retardation. Surprisingly, even hearing loss and socioeconomic level were unrelated. The investigators hypothesize that retardation in both receptive and expressive language may result from the parents' failure to accept early distorted speech attempts, thus depriving the child of normal feedback and reinforcement. However, this presumes that the early speech attempts are distorted; and this may not be true for the increasing numbers of cleft-palate children whose speech acquisition proceeds according to a relatively normal pattern.

We know little of the origins of reduced language skills in children with clefts of the lip and palate, and even less about these abilities in children with other dentofacial deficiencies. The fact that they seem to occur throughout the range of mental and speech abilities suggests that we should be looking for explanations in psychic phenomena, perhaps moving backwards in time to the early deprivation of oral satisfaction, parental feelings, emerging self-concept in given environments, management of infant hearing problems, hospital and surgical experience, family and peer relationships. Whatever the explanation is, it is sure to be complex, at least as complex as the development of language in the normal child, about which we are still largely descriptively oriented.

INTELLIGENCE

The Handbook of Congenital Malformations (Witkop, 1967) lists 80 different syndromes that involve facial disfigurement of varying degrees. Of these 80, 21 are reported to be associated with mental retardation. Mental retardation is implied in 11 other conditions. This suggests that mental retardation may be a problem in approximately 40% of congenitally determined maxillofacial disturbances. This should not be interpreted to mean 40% of all the patients suffering from the various syndromes. There is an apparent tendency for the incidence of mental retardation in a given syndrome to increase with the severity of the facial problem. This might lead to the cautious conclusion that evaluation of mental abilities should have a major role in the clinical assessment of patients with severe facial abnormalities. It often does not, however, solve the problem of the origin of the retardation. Does it emerge as a part of generalized deficiencies or is it the result of depressed ability to function up to capacity? The answer to that question probably depends upon many factors yet to be investigated.

Ruess, Pruzansky, and Lis (1965) studied by a variety of methods intellectual development in 12 patients with the oral-facial-digital (OFD) syndrome in recognition of the fact that the majority of reports in the literature emphasize mental retardation as one of the characteristics of that syndrome. They tentatively concluded, from their evidence and from careful evaluation of previous reports, that only between one-third and one-half of patients with OFD syndrome are really mentally defective. They state, wisely, that "when published data emphasize only certain aspects of phenomena that require refined multidimensional study, the issues cannot but regrettably become more confounded."

This same statement may be made in connection with the study of the mental abilities of children with cleft palates. The literature for parents frequently advises parents that the children are "normal" in this regard or are "like other children"—whatever that may mean. However, a number of studies varying in sophistication (Billig, 1951; Drillien, Ingram, and Wilkinson, 1966; Goodstein, 1961; Illingsworth and Bush, 1956; Lewis, 1961; Means and Irwin, 1954; Munson and May, 1955) suggest that such children, particularly those with clefts of the palate only, are mildly depressed in mental development, with means tending toward low average rather than average. Rattner, Carter, and Pelkey (1958) would dispute these findings, but they studied only 17 children over the age range of 6 to 15 using the Wechsler Intelligence Scale for Children. Their population was too small, their age span too great, and their standard deviations too high to put final faith in the results.

Cervenka and Drabkova (1965) found that 42 children with clefts of the lip, palate, and unilateral lip and palate showed normal intelligence or average IQs within the expected range. Their 19 with bilateral clefts, however, had a mean IQ of only 87. These findings are uncertain because 5 of the 19 children had IQs of 68 or below, and none of the children in the other groups was that low. Sampling errors may have influenced the results.

Ruess (1965) compounded the problem somewhat by his study of 49 children, aged seven to 12, with cleft palate and 49 nearest-age siblings. The former were significantly lower in verbal and full-scale IQs but showed no difference in performance IQs. The two groups were similar in reading and spelling skills, figure drawings, and school progress. This study suggests that the slightly lower mental capacity that is usually found in groups of children with clefts may relate to verbal functioning. McWilliams and Musgrave (1966) substantiate this point of view somewhat in their study of 168 cleft-palate children divided into three groups on the basis of speech adequacy. Children with completely normal speech and those with normal voice quality accompanied by consonant articulation errors were comparable to each other and showed mean Binet IQs of 109 and 108 and mean WISC IQs of 104 and 105 respectively. However, children with hypernasal speech had a mean Binet IQ of only 97, a statistically significant difference. While differences on the WISC fell short of significance, the trend was the same.

Synthesis of the literature in the area of mental development leaves little doubt but that children with cleft lip and palate are distributed throughout the total range of abilities but that their mean IQ tends to be somewhat lower than that of a normal population—although this lower mean falls within the limits of "average." Far less clear is the origin of the intellectual depression—and perhaps we should think of it in just those terms until we understand it better. It would be worthwhile to extend these studies to encompass time, parents, school performance, ultimate social adjustment, vocational success, and life patterns in adulthood. It is premature to conclude that this intellectual depression is permanent and irreversible. It may relate primarily to expressive speech skills and to psychic phenomena that are presently purely speculative.

DISCUSSION

Investigation of the literature associated with the psychosocial aspects of dentofacial abnormalities leads to the conclusion that much of the material is still based upon limited clinical observations, some of which have been made quantifiable by the introduction of observational rigor, the use of tests, and attempts at statistical verification. These efforts have tended to be associated with particular facets of the problem. Thus, there is an impressive amount of information about the parents of disfigured children, and about the personalities of people who have these handicaps, their language behavior, and their social and intellectual functioning. The difficulty with organizing this vast body of work into a coherent whole lies in the fact that sampling errors are almost built into the designs of most of the studies. Psychologists, psychiatrists surgeons, speech pathologists, and an occasional dentist have studied the patients in their particular centers, often forgetting the variables associated with geographic, ethnic, educational, economic, occupational, social, and familial backgrounds; variability in treatment plans and procedures; lack of uniformity in the skills of the specialists who carry out the procedures; and lack of homogeneity in the disorders themselves. All of these are apparent variables that make it difficult to generalize findings from one population to another unless results have been replicated in various studies. As if these hurdles were not burdensome enough, we also must face the reality of hidden variables. These cannot be controlled because we do not know enough to isolate them, and they may operate disproportionately between and among groups. These factors would help to explain some of the confusion in the literature.

A second area of concern in psychosocial investigations is that of methodology. Simply designed investigations have been the usual rule even though many researchers recognize that combinations of conditions may constitute "syndromes of influence" in the development and maintenance of life patterns, which, viewed from a single reference point, may be inaccurately understood. Future research, if it is to go very far beyond clinical observation and case report, will have to be designed to look at people in all their complexity with full recognition that simple investigations seeking correlations or differences in populations will seldom provide definitive information about the workings of man. We now are able to see that, with the possible exception of psychoanalytic theory, we lack the theoretical frameworks necessary for the organization of the masses of empirical data available. This same limitation places restraints upon our ability to ask appropriate questions. It may not be premature to suggest that we are beginning to be ready to move into more sophisticated work that will require the observational talents of the clinician along with his experience in asking the right questions; but it will necessitate, too, the use of design experts who are also knowledgeable about the vastness of the problems awaiting resolution.

With these precautions in mind, we can see the necessity for longitudinal studies that can say something about the adult and his sphere of influence—the adult who may have begun life with a traumatized mother; who may have produced a distorted human figure drawing when he was six, demonstrated a notable lack of creativity, and scored poorly in language measures; and who probably encountered adverse social attitudes. He may even have wet the bed and told stories reflecting oral aggression in the preschool years. The final measure of the significance of these grim facts, however, is their predictive value in the life of a developing human being. If it can be shown that they do provide the clues we sense clinically, then we must learn to deal with them so that the process can be reversed and the child can be helped to become a well adjusted adult. In short, we still have far to go in learning how to treat the patients with the deficits we are beginning to learn about. However, it may be well to remember in this regard that our goals for the facially disfigured cannot exceed the goals we recognize for people in general; and this may constitute the source of our real dilemma. We still know so little about people that our studies of special groups are in serious jeopardy at the outset. It is apparent, too, that we are largely ignorant of society's influence in shaping human behavior and of its possible subtle mechanisms for determining the precise roles various individuals are expected to play.

The state of the art is unsettled, unsure, and immature. It looks somewhat expressionistic, with each investigator tending a bit to express his own ideas and attitudes. We would be unwise, however, to reject an investigator because of this. Knowledge begins first with observation, but the maturing process with all its testing and proof is part of the picture as well. There are more well designed and executed plans of attack now than was the case even ten years ago, but the evidence of our occasional regression to less mature behavior persists. In another ten years, I suspect that we will look a little better than we do now. We will have learned together and will have added some fragments and pieces that cannot now be envisioned; but we will not have reached perfect understanding or found permanent solutions to our dilemma. Our concerns will persist for as long as man, in his changing world, remains on earth.

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ORAL SENSATION AND PERCEPTION: A SELECTIVE REVIEW

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Failures in oral sensory and perceptual experiences often indicate nervous system pathology. Recent interest in oral sensation and perception, however, goes beyond its diagnostic value. The role of sensory and perceptual experiences in developing and regulating oral motor performance is currently being studied. It is now apparent that the finely coordinated motions of the mouth do not result from an array of spatially and temporally patterned motor impulses released blindly into the efferent network from high centers in the nervous system. Motor patterns are modified and restructured along the control pathway at various motor relay regions in accordance with information received from peripheral sensory resources (Paillard, 1960). Various theories attempt to explain some aspects of oral motor control as a feedback-level mechanism. Representative of such orientations are those concerned with speech production. It is not my intent to endorse any particular theory of speech control or to present all aspects of controversies surrounding such theories, nor is it to be implied by that proprioceptive feedback is always a major component of the theory.

Fairbanks (1954) presented one of the most widely cited models of speech production calling for sensory monitoring of motor activity. The essentials of this system are:

> feedback of the output to the place of control, comparison of the output with the input and such manipulation of the output producing device as will cause the output to have the same functional form as the input. (p. 135)

More recent concepts of speech production systems give sensory processes relatively little attention. MacNeilage (1970) notes that

> at no point in these models was the active use of information from ongoing movement accorded a role which affected their form in a critical way, even though the possible influence of such mechanisms was sometimes noted. In fact, one of the main properties of these models is that the command system is independent of the peripheral response apparatus. (p. 186)

One can argue that the more recent models have been designed to account primarily for the motor control of the serial ordering of speech; such constructs attempt to specify the nature of the motor units at higher-to-lower levels in the articulation process. Recently MacNeilage has recognized that it may be necessary as well as enlightening to specify certain sensory mechanisms which may be operating, in order to explain context-dependent articulatory phenomena.

The extent to which sensory feedback processes have been included in models of the speech system varies with the nature of the model. Henke (1967) suggests that proprioceptive feedback provides the mechanisms whereby the timing or rate of articulatory activities is accomplished. As an example of the use of this kind of feedback Henke describes the production of a stop in which ongoing articulation waits until contact between articulators (closure) is attained and then uses awareness of this happening, presumably through proprioceptive feedback, as a trigger for further articulatory activity. This view, of course, is not supported by some recent coarticulation data which shows that articulatory gestures often do not depend on the execution of antecedent articulatory events.

MacNeilage (1970), discussing the sequencing of articulatory movements, refers to the results of oral stereognosis studies as evidence that persons

> can integrate complex patterns of tactile and motor information to make accurate judgments of the spatial characteristics of the stimulus objects. (p. 188)

He reasons further that

> it is likely that by such integration of motor information with concurrent tactile and other somesthetic and kinesthetic information (and auditory information) the language learner builds up an internalized spatial representation of the oral area. Within this representation he is able to signify points which must be reached for the articulation of various speech sounds, and because of the constant association of motor activity with development of the representation, he is readily able to specify the motor actions necessary for an articulator to reach a given target point. (p. 188)

Perkell (1969) views the speech production mechanism as composed of "two neuromuscular systems with different behavioral characteristics responding in general to different feedback." In his view of the articulation system, vowels are produced through the action of a slow extrinsic tongue muscle network under the primary influence of acoustic and myotactic feedback. Consonant production, on the other hand, is thought of as being produced by the combined function of the fast-acting intrinsic, as well as the slower extrinsic, muscle systems and is regulated by intraoral air pressure and tactile feedback. Ladefoged (1967) has also hypothesized that the production of vowels depends more on auditory monitoring than do the consonants, which depend more on oral sensory feedback.

Ladefoged (1967) questions whether the perception, as well as control, of speech is related to proprioceptive feedback mechanisms. Liberman (1957) presented a model of phonological perception in which speech production and perception are considered as two aspects of the same process. This model, which has resulted in the formation of the "motor theory" of speech perception, maintains that the acoustic stimulus leads to a covert articulatory response, the proprioceptive feedback of which leads to the discriminative event we call perception. The rationale underlying this theory has been expressed by Liberman and his associates (1961) as follows:

> We believe that in the course of his long experiences with language a speaker (and listener) learns to connect speech sounds with their appropriate articulations. In time, these articulatory movements and their sensory feedback (or, more likely, the corresponding neurological processes) become part of the perceiving process, mediating between the acoustic stimulus and its ultimate perception. (p. 177)

If this theory is tenable, then relating a listener's perception of speech exclusively to the acoustic correlates of the auditory sensation overlooks a potentially important perceptual system, namely, a listener's proprioceptive (kinesthetic) feedback mechanism.[1] To Ladefoged (1967), sole attention to the acoustic stimuli and neglect of a listener's own experiences as a producer is

> rather like trying to discuss the visual identification of the shapes of tables and chairs exclusively in terms of the photic stimulation of the retina, and without recognizing that the observer might organize his perceptions in terms of objects with which he is familiar. (p. 162)

The acceptance of views about speech processes such as those described must be based on the demonstration of an oral sensory system in which the receptors are capable of providing the speaker with accurate information about his articulators, and a neural system which is capable of relaying information received at the periphery to higher centers in the nervous system. In addition, support for the sensory component of the theoretically proposed systems of speech production should be available in evidence collected from the study of persons in whom the oral sensory system functions at different levels of proficiency.

In this paper I will review evidence reflecting on the tenability of the speech system models. This information has been drawn primarily from neuroanatomic and physiologic studies as well as from investigations that have used the following research approaches: (1) tests of oral sensitivity; (2) detailed studies of persons with sensory pathologies; and (3) experimentally induced sensory deficiencies. Finally, the paper will highlight certain areas requiring additional research.

NEUROANATOMIC AND PHYSIOLOGIC STUDIES

Cutaneous Receptors

There are a wide variety of receptors throughout the oral mucosa. Grossman and Hattis (1967) summarized the distribution of these sensory endings and made some general statements about the neurohistologic makeup of the oral mucosa. They indicated that despite the diversity in size of sensory endings

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[1] For a critical review of the motor theory of speech perception, see Lane (1965).

noted throughout the oral mucosa, and despite specific variations of innervation from site to site, there is a gross similarity in receptor form and in the pattern of innervation of the several oral surfaces. They also noted the declining progression of nerve-ending occurrence, generally from the front to the rear of the mouth, that is evident particularly in the tongue and hard palate, and that lingual sensory terminations are more numerous on the dorsal than on the inferior aspects. Grossman and Hattis commented that, in their view, low threshold to sensory experience exhibited by the mouth, when compared with that of skin surfaces, may be due to the presence of epithelial fibrillar extensions which are limited to moist mucous membranes.

With few exceptions, the presence in the oral mucosa of the receptor types and distributions described is accepted. The contribution of such information, however, toward understanding sensation and perception is still unresolved. According to Von Frey's classical concept, cutaneous sensations such as pain, cold, warmth, and touch are subserved by specific receptors (Rose and Mountcastle, 1959). Research at Oxford University (Sinclair, 1955) which failed to relate specific endings to certain cutaneous modalities in several skin areas did not support the classic concept. The theory offered instead is known as the Pattern Theory and states that different cutaneous sensations arise not as a result of stimulation of a specific receptor type but rather because different stimuli affect the same receptor complex in a different manner.

As Rose and Mountcastle (1959) commented, however,

> one hesitates to accept as a solution to the vexing problem of the morphology of the encapsulated endings a declaration that virtually all morphological differences between them are either insignificant or due to artifacts of the technique. (p. 390)

More recently Melzack and Wall (1962) attempted to resolve the differences between the specific receptor and pattern theories by proposing that

> receptors are specialized physiologically for the transduction of particular kinds and ranges of stimuli into patterns of nerve impulses . . . and that every discriminable different somesthetic perception is produced by a unique pattern of nerve impulses. (p. 342)

This view has gained relatively widespread acceptance.

Muscle Receptors

It seems clear that information from cutaneous receptors reaches a cortical level via the trigeminal lemniscal system and that tactile information surely must contribute to conscious knowledge of articulatory position, or kinesthesia. However, since running speech is certainly a highly automated motor act, it is appropriate to ask whether the oral structures contain receptors capable of contributing to reflex knowledge of articulator position, or proprioception. Receptors such as those embedded in muscle spindles are known to have the capability to act in such a manner. The muscle spindle is a specialized receptor unit in the muscle which contains polar intrafusal muscle fibers and central noncontractile sensory endings. The spindle intrafusal fibers are innervated by small-diameter gamma motoneurons, and the spindle sensory neurons end in synaptic relations to the alpha motoneurons innervating the main body of the muscle. In this way a reflex arc is formed whereby a gamma motoneuron firing causes intrafusal fiber stretch on spindle sensory endings, which, in turn, fire and activate alpha motoneurons. Consequently, extrafusal fibers contract until spindle sensory stretch is eliminated. This functional mechanism has been referred to as the "gamma loop."

Controversy exists both about the presence of muscle spindles in oral structures such as the tongue and about their possible importance in oral sensory functioning. While Blom (1960) found no such receptors in the tongue, Cooper (1953) observed muscle spindles in the region of the tongue proximal to the tip. Rose and Mountcastle (1959) cited two pieces of evidence which argue against the inclusion of muscle spindles as a kinesthetic sensing device. First, the discharge rate of muscle spindles has been shown to be unrelated to muscle length, whereas joint receptor discharge rate seems to relate to muscle tension. Second, spindle afferents seem to relay to the cerebellum but not to the postcentral cortex. Thus, information from muscle spindles is not available for conscious introspection in motor learning (Shelton, in press). Matthews (1964) reported that it is widely accepted that muscle spindles are not primarily important for any contribution they make to conscious awareness of position.

Investigators who attach some importance to muscle spindles in the control of speech production, however, generally have not believed that conscious perception of position is a necessary requisite. Rather, the muscle spindle is thought to be important not in the sense that it is like primary sensory receptors but because it is a structural component of the gamma efferent loop. MacNeilage (1970) postulated that the motor commands for invariant target positions (states of muscle contraction in the vocal tract) may be issued via gamma motoneurons.

He states:

> As a gamma command of a given magnitude will always require the main body of the muscle to assume the same length in order to eliminate stretch on the sensory fibers, the gamma loop appears to be a mechanism whereby a muscle can attain the same position regardless of its length preceding the gamma command. (p. 191)

If the gamma loop is to function in the manner MacNeilage hypothesizes, an explanation of the inevitable "time loss" in neural transmission around the loop is necessary. Matthews (1964) discusses the gamma loop delay problem and draws an analogy between the gamma efferent system and inanimate servo-control systems in which time delays, and their resultant system oscillations, are counteracted by mechanisms within the loop which predict the nature of the "end" signal. With specific reference to the gamma loop, Matthews views the primary afferent muscle spindle endings as a potential compensatory mechanism for the time delay, since they are responsive to the velocity of muscle spindle stretch and capable of using such information about the rate of muscle change

> to "predict" the length of the muscle after the delay time of the reflex, and so ensure that the response will be appropriate to the time when the reflex becomes effective, rather than to the earlier time when the reflex was initiated. (p. 278)

If this latter view is correct, the gamma loop mechanism may be an important component in oral sensory functioning for speech.

An example of the role that proprioceptive feedback might play in the control of speech activities is contained in the work of Kirchner and Wyke (1964, 1965). Their investigations have revealed that the larynx is equipped with two distinct intrinsic mechanoreceptor reflex systems, one a phasic reflex system which is driven from rapidly adapting receptors located in the capsules of the laryngeal joints (the articular system) and the other a tonic servoreflex system which is driven from slowly adapting receptors embedded within the muscles themselves (the myotatic system). These systems clearly play a part in the continuous and precise adjustment of laryngeal muscle tone during phonation.

In brief, Wyke (1967) has stated that, once the column of air is set into motion within the larynx, the laryngeal muscles and the cartilages to which they are attached are deflected from their preset phonatory posture:

> It is the function of the articular and myotatic reflex systems within the larynx to return the muscles promptly to the desired coordinated pattern of contraction and relaxation, and to keep them there, during the period of phonatory air flow.
>
> Finally, once the sound becomes audible, further adjustments are made (both voluntarily and reflexly) to the tone of the respiratory, laryngeal, buccopharyngeal and labio-glossal musculature in response to acoustic monitoring of the subject's own vocal performance. (p. 13)

The work of Kawamura (1965) on the mandibular musculature also supports the presence of a sensory control mechanism for motor activity. He reports:

> A noxious stimulus to the oral and perioral structures will easily induce the jaw-opening reflex. There are close connections between the sensory nucleus of the trigeminal nerve and its motor nucleus which innervate the jaw muscles. Noxious stimuli to the oral structures have some inhibitory or facilitatory effects on the motor nucleus of the trigeminal nerve, and oral sensations may regulate the jaw muscles activities by means of this feedback system. (p. 182)

In Kawamura's view, motor control of the jaw muscles is primarily a function of sensory processes originating within the temporomandibular joint (TMJ). Specifically, he believes that information from the mandibular sensory systems is transmitted to the trigeminal nuclei and that close connections exist between the sensory nucleus of the trigeminal nerve, which receives the afferent signals, and its motor nucleus, which innervates the mandibular musculature. Kawamura (1961) has also reported that certain types of oral stimuli tend to inhibit or facilitate motor activities of the jaw. Thus it appears that the sensory experiences of the TMJ may regulate and otherwise control mandibular motor activity by means of a feedback system. More specifically, the sensory mechanisms of the TMJ are hypothesized to play an active role in regulating the tension and length of jaw muscles, the position of the mandible, the maintenance of the "free-way space" (oral aperture), and the dynamics of mandibular movements.

TESTS OF ORAL SENSITIVITY

There is a rapidly growing body of literature dealing with the oral sensory abilities of pathological groups of speakers. The underlying intent of such investigations has been to establish whether or not a measurable relationship exists between oral sensory functioning and speaking proficiency. The most common method of assessment has been that of oral form recognition. In a typical test of oral form recognition, a subject is asked to orally manipulate a previously unseen three-dimensional form, and to identify that form from a group of visually presented forms. Tests developed by various investigators (the development of oral form-recognition tests has a short but extensive history which has been reviewed recently by Shelton, 1970) have differed in number and type of forms used as well as the exact nature of the task required of subjects. These methodological differences place certain limitations on the comparison of results that I shall describe, and may account for some of the conflicting results and conclusions.

The speakers studied most extensively with tests of oral form recognition are those with articulation defects in the absence of known organic or structural pathologies. Four separate investigations (Moser et al., 1967; Ringel, Burk, and Scott, 1968; Ringel et al., 1970; Weinberg, Lyons, and Liss, 1970) have demonstrated that articulatory-defective speakers have more difficulty with oral form recognition than do their normal-speaking controls. This has been demonstrated for children as well as adults (Ringel et al., 1970). In addition to the generally positive relation between articulation skill and oral form performance, it has been demonstrated that measurements of oral form discrimination can differentiate between degrees of articulatory proficiency that have been established a priori by independent means (Ringel, Burk, and Scott, 1968). Thus, children and adults with mild articulatory problems make more errors than normals, but significantly fewer errors than speakers with more severe articulation problems. In an interesting investigation, Locke (1968) showed that children with good oral-form scores are better able to learn unique articulatory tasks than children with poor oral-form scores. Contrary to these findings, two investigations have been reported that failed to demonstrate clear relationships between articulatory performance and oral-form skill (Moser, LaGourgue, and Class, 1967; Arndt, Elbert, and Shelton, 1970).

Oral form recognition also has been employed to assess sensory abilities in cerebral palsy, cleft palate, and stuttering. In a group of athetoid patients, Solomon (1965) reported that form recognition was positively correlated with ratings of chewing and drinking ability and with articulation scores. In the Moser, LaGourgue, and Class (1967) study, cerebral-palsied adults made oral form judgments which were significantly poorer than those of their normal controls. They also reported that a group of stutterers made poor oral form-recognition scores. Cleft-palate adults had difficulty making oral form judgments in an investigation by Hochberg and Kabcenell (1967), while Mason (1967) found that normal and cleft-palate speakers behaved similarly.

A less-frequently employed tool for evaluating sensation in pathological speakers is two-point discrimination. Schliesser (1965) found two-point discrimination in the lip to be positively correlated with speech defectiveness in spastic hemiplegic children. Patients with muscular dystrophy and concurrent speech difficulties demonstrated larger limen and variability values than did normal subjects, in a recent investigation (Ringel, 1970). On the other hand, Rutherford and McCall (1967) were unable to show significant two-point limen differences between normal and cerebral-palsied children, and Addis (1968) found that limen values for stutterers are like those of normal speakers.

Examples of the application of other methods of assessing oral sensation in pathologic groups can be found in the literature. These include methods designed to measure tactile acuity, texture discrimination, localization, and pattern recognition, kinesthetic pattern recognition, and vibrotactile sensitivity and scaling (Rutherford and McCall, 1967; Fucci, 1968). In general, these methodologies have not discriminated between pathologic and normal speakers as well as oral form testing procedures.

As noted, oral form-recognition testing most often has been employed in evaluating sensory capabilities in clinical groups of speech-defective individuals. It is probably true that the factor of clinical expediency explains, in part, the widespread use of oral form recognition in assessing sensory abilities. In most of its forms, the test is relatively easy to administer and can be accommodated by fairly young children as well as by individuals with severely handicapping conditions such as cerebral palsy and muscular dystrophy. More interesting, however, is the attempt to explain why this task seems to relate to a skill such as speech. Since many studies of oral form recognition have been concerned largely with methodological questions and factors such as test reliability, they have not asked this question. A notable exception is found in the writing of Shelton, Arndt, and Hetherington (1967). These authors recognized the necessity of attempting to describe both anatomically and physiologically the nature of the task of oral form recognition, and state, "The ability to recognize forms orally requires the integrity of both peripheral receptors for touch and kinesthesis and also central integrating processes." We (Ringel et al., 1970) have also alluded to this problem in a statement about performance on an oral form-discrimination task:

> It is not enough to believe that the severity of an oral discrimination disability increases merely as the total error score increases; identification of the level of discrimi-

> nation failure is crucial for understanding the sensory deficit in question and its potential effect on organized motor activities of speech production. (p. 4)

Variables which appear to affect oral sensory performance also have been investigated. For example, performance levels have been shown to improve with increasing age through midadolescence, when these levels seem to stabilize, as demonstrated by Arndt, Elbert, and Shelton (1970). McDonald and Aungst (1967) obtained similar results for oral form recognition and demonstrated that mean score decreased considerably in a geriatric population. We (Ringel et al., 1970) reported that articulatory-defective adults performed better in oral form discrimination than did normal-speaking children with a mean age of eight years. These facts strongly suggest that age facilitates performance in oral form discrimination. Maturational indices can be discussed as having at least two major components—one related to physiological abilities as such, and the other involving "higher orders" or organization of input to the organism. The adult may be more proficient in stimulus exploration than the child because of superior motor abilities that permit more appropriate manipulation of the stimulus forms. Similarly, the increased ratio of oral-cavity size to stimulus-form size in the adult as compared to the child may favor more adequate manipulation. Other factors which may favor the adult in discriminating form include his more developed motivational attitudes, and his attention and retention spans.

Testing of the oral region has shown that the oral cavity does not demonstrate uniformity in its mode of response to stimulation. Certain regions of the oral cavity are more capable of making perceptual evaluations than others, and different stimuli depend on different oral regions for their successful evaluation. In general, research in two-point discrimination indicates that the front of the mouth is more sensitive than its posterior regions and that increased discriminability exists at the midline of the structure (Ringel and Ewanowski, 1965). Grossman, Hattis, and Ringel (1965) reported that the lip exhibited more sensitive tactile thresholds than the incisive papilla. However, the tongue is capable of more accurate texture judgments than the lips (Ringel and Fletcher, 1967). McCall and Kirkley (1967) demonstrated bilateral symmetry for tactile thresholds in the lower lip. Arndt, Elbert, and Shelton (1970) observed that fewer forms were identified when explored by the lips alone than the entire oral cavity and tongue. This seems to indicate that oral form recognition is a skill for which lingual sensitivity and manipulaton are paramount. Some recent research on the palate by Shelton et al. (in press) would seem to indicate that kinesthesia is poorer for movement of the palate than for other parts of the body.

In general, the results of studies which have tested various parameters of oral sensitivity indicate that the progression from maximal to minimal discrimination involves the lingual, labial, and palatal structures, in that order, and that the lingual region rivals the fingertip in relative sensitivity. An evaluation of these findings has been reported (Ringel and Ewanowski, 1965). The reviewed literature indicated that

> the discriminatory ability of an area varies directly with the size of its cortical and thalamic projection areas . . . the relative volume of tissue of the thalamic relay nuclei and of the post-central cortical gyrus which is devoted to a given peripheral area is directly related to the density of peripheral neural innervation of that region and inversely related to the size of the receptive fields contained within this peripheral area. (p. 395)

The finding of greatest sensitivity for the relatively mobile oral structures is also compatible with the observation that a correspondence exists between the mobility of a structure and its discriminatory ability (Silverman, 1961; Shewchuk and Zubek, 1960).

STUDIES OF PERSONS WITH SENSORY PATHOLOGIES

Intensive study of individual cases can provide insight into the role of oral sensation and perception. Such an investigation, of a young woman with a congenital sensory deficit, has been reported. Data from medical and developmental history, results of physical and neurological examinations, as well as results of nonvocal motor testing and histological investigation, are presented in some detail by Chase (1967). Rootes and MacNeilage (1967) reported the results of tests of speech perception, electromyography of the oral area, and phonetic analysis of the patient's speech. Finally, Bosma (1967) has presented palatographic and cineradiographic data. The integration of such extensive data, and somewhat less detailed data for another youngster with a similar oral sensory deficit (Bosma, 1967), bring to light a number of observations of potential significance in understanding sensation as it relates to skilled motor acts such as speech. For example, these patients' speech was described as minimally intelligible with consonant production being severely impaired; yet both were able to perceive light touch throughout the oral area. Such observations indicate that looking at types of sensations other than those embodied in "light touch" is requisite to understanding speech monitoring. In this respect it is interesting to note that these patients were almost totally unable to perform on tasks of oral form recognition which, as discussed earlier, is often viewed as a skill requiring fairly high-level sensory function.

In one of these patients, the relation between speech perception and production also was investigated (Rootes and MacNeilage, 1967). This study was prompted by interest in the motor theory of speech perception discussed earlier. The investigators reported

> evidence in this subject that production and perception are interrelated, namely in front vowels and voiced stop consonants, where the most efficiently produced phones (/i/ and /b/) are also the ones most successfully identified. (p. 317)

Rootes and MacNeilage urged caution in interpreting these results, however, since the patient's perception of speech in informal conversation was considerably better than would be predicted, in accordance with the motor theory, from her speech production alone. In another interesting case study, McDonald and Aungst (1970) comment on "the apparent independence of oral sensory functions and articulatory proficiency." In their study of a cerebral-palsied patient they found good oral sensory capacities but very poor speech patterns.

EXPERIMENTALLY INDUCED SENSORY DEFICIENCIES

Since 1960, a series of studies have attempted to delineate the role of sensory mechanisms in speech through the use of nerve-blocking techniques that are assumed to induce temporary peripheral sensory lesions in the oral cavity (McCroskey, 1958; McCroskey, Corley, and Jackson, 1959; Weber, 1961; Ringel and Steer, 1963; Ladefoged, 1967; Schliesser and Coleman, 1968; Thompson, 1969; Gammon, Daniloff, and Smith;[2] and recent work, manuscript in preparation, by Cheryl Scott and this author). The need for tests of the assumptions underlying this research is discussed later in this paper.

A careful comparison of these investigations reveals certain points of agreement as well as disagreement. All investigators agree that speech resulting from tactile-kinesthetic deprivation remains highly intelligible. In other words, listeners have little difficulty "understanding" the speech of sensory-deprived talkers. This seems to be true for both single words and connected speech material and applies also to those conditions in which sensory deprivation and auditory masking are combined. This finding is of particular interest in light of the observations reported earlier for the two patients with the sensory system pathology whose speech was minimally intelligible. Since the intelligibility of speech under anesthesia is minimally affected, while it is seriously degraded in persons with congenital oral sensory deficits, it may be profitable to distinguish between anesthetized persons who have had normal oral sensory experiences in the past and those patients who have never experienced normal sensation in the mouth; or, at a different level, between those patients with a central sensory deficit and those with a loss of peripheral sensation. It does appear that in the short-term sense, the speech-producing mechanism is capable of maintaining a high degree of integrity (as reflected in speech intelligibility) in the presence of an interruption in its usual sources of information. Failure to induce speech alterations through anesthetization of the type observed in persons with congenital sensory deficits is provocative "in view of the stress placed by current speech control theory upon the importance of auditory and tactile feedback" (Schliesser and Coleman, 1968).

Studies also agree that tactile-kinesthetic deprivation results in certain phonetically observable changes and that consonants generally are perceived as being more affected than vowels. While the observations about vowels have been made a number of times and generally are accepted, this finding should not be interpreted to mean that the anesthetization procedures affect articulators less during vowel production, but rather may be merely a reflection of the

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[2] Gammon, S. Ann, Daniloff, R. G., and Smith, P., unpublished work. Personal communication (1970).

fact that there is a wider degree of articulatory latitude which is phonetically tolerable in vowels. Most studies looking closely at the types of articulatory errors have pointed to the relative vulnerability of stops and fricatives to sensory deprivation. Similarly, the performances of subjects on certain nonspeech tasks indicate that diadochokinetic rates are not affected by oral anesthetization but that performance on oral form recognition tasks deteriorate under such conditions (Schliesser and Coleman, 1968; Gammon, Daniloff, and Smith, cited in footnote 2).

A major area of disagreement exists in the specific description of articulatory changes under anesthesia. McCroskey (1959) reported that most articulatory changes were of the substitution type. Gammon, Daniloff, and Smith (see footnote 2) concur with McCroskey and state that "the majority of mistakes occur as a result of changes from one manner or place to another rather than within such classes." On the other hand, three investigations have shown that articulatory changes are largely distortions. Ringel and Steer (1963) reported that listeners described most errors as distortions. Ladefoged (1967) stated that "one consonant was seldom replaced by another different enough to change the meaning, although this is a very common type of speech defect." Finally, in unpublished work now in preparation at Purdue University (Cheryl Scott and Ringel), it is observed that the overwhelming majority of articulatory changes under anesthesia were of the distortion type.

Whereas most studies noted previously used nerve-blocking procedure to achieve states of oral-region sensory deprivation, literature also exists on studies which used topical anesthetization techniques (Ringel and Steer, 1963; Henja, 1962; Ladefoged, 1967; Weiss, 1969). In general, these studies have reported that topical anesthetization has a minimal effect on speech accuracy. The one notable exception to this consensus is found in the work of Ladefoged (1967), who reported "very disorganized" although intelligible speech under topical anesthesia conditions. If the assumption is plausible that "light touch" is somewhat akin to the type of sensation that is disturbed in topical anesthetization and the case histories reported earlier are recalled, in which the patients' speech was poor but light touch sensation relatively normal, the role of light touch in speech monitoring must be questioned.

Perhaps the most interesting aspect of sensory deprivation investigations is the explanations of the data. McCroskey, Corley, and Jackson (1959), like most of the later researchers, observed that semivowel and nasal-consonant production was relatively unaffected by tactile-kinesthetic deprivation. They reasoned that since semivowels and nasal continuants are distinguished from other consonants mainly because of a durational difference (that is, they are longer), there exists a critical duration where monitoring responsibilities are shifted from tactile to auditory channels. This reasoning seems untenable, since it is not clear that fricatives, the class of consonants probably most affected by deprivation, are "short" sounds.

In earlier work (Ringel, 1962) no attempt was made to explain the specific effects of tactile-kinesthetic deprivation by itself. Rather, speech trends were explained in terms of general sensory alteration, both tactile-kinesthetic and auditory. Theoretical explanations were based on the hypothesized existence and accuracy of Fairbanks' servosystem theory of speech control. Articulatory inaccuracy was hypothesized to result from the comparator's inability—in the absence of sensory information—to perform its matching operation. Unable to compare actual output with intended output, the system is thus incapable of resolving errors. Decreased rate and increased amplitude of speech were attributed to the system's attempt to restore homeostasis to the speech process. Thus, the speaker slows down in an effort to increase the available time in which he might learn something about his speech. He speaks more loudly in an effort to compensate for disorganized information by increasing the total amount of information.

Ladefoged (1967) accounted for the differences in the effects of tactile versus auditory deprivation by ascribing distinctive functions to both channels. Vowel quality, nasality, and pitch typically are monitored by reference to their acoustic properties, while consonant production is monitored through the oral sensory channel. Gammon, Daniloff, and Smith (see footnote 2) have looked to the underlying articulatory differences between consonants in their attempts to explain the differential effects of sensory deprivation. The tendency for intended fricatives to become stops was expected, since the stop open-close articulation requires much less articulator precision and feedback than the precise constriction requirements for fricatives. These authors also reasoned that vowel production is monitored by kinesthetic feedback (rather than tactile feedback), which they did not consider to be disrupted by the nerve-block procedure. Similarly, stress/juncture production was hypothesized to depend on kinesthetic feedback.

The tendency to assign monitoring responsibilities for different types of articulatory events (for example, vowels and consonants) to separate sensory channels is premature in light of available evidence. Before accepting such a notion, considerable physiologic evidence on the nature of articulatory changes under conditions of deprivation is needed. In the production of a stop, for example, we need to know whether a speaker uses tactile information about a closure, as Henke (1967) hypothesizes, or if he relies more on some sense of intraoral pressure feedback. It is also important that the experimental data be consistent with clinical observations of the speech of the adventitiously deafened. To illustrate this latter point, Ladefoged's (1967) observation that consonants depend on tactile feedback would not explain the numerous consonant misarticulations characteristic of the deaf.

Two general statements can be made about the early tactile-kinesthetic deprivation studies. First, the investigations were, in effect, merely demonstrations of the often hypothesized relationship between tactile-kinesthetic sensation and speech production. That is, early tactile-kinesthetic deprivation studies demonstrated that speech changes result from oral sensory alteration. Secondly, as noted in the explanations of the differential effects of deprivation, the tendency was to assign monitoring responsibilities for unaffected articulatory events to other sensory channels presumed undisturbed by the anesthesia (auditory or kinesthetic). This reasoning reflects the belief that all types of articulatory activities are monitored by some sensory channel, and is also another indication of the general acceptance of the speech servosystem theory.

It is conceivable, however, that other explanations may be needed to explain the differential effects of sensory deprivation on speech. Contrary to the views expressed in the Fairbanks model, it is possible that some motor commands received by the articulatory apparatus are not altered by the nature of tactile-kinesthetic information. Scott and Ringel have noted the importance of this issue and have hypothesized that a closed-loop tactile-kinesthetic feedback system may not operate for all types of articulatory activities. The presence of "open loop" control for certain articulatory activities along with "closed loop" control of other articulatory movements has also been theorized by MacNeilage (in press). The observation presented previously with regard to the case studies would seem to support this view. That is, tactile information about articulatory contacts made during the production of some consonants may not contribute crucial data to the feedback mechanism operating for speech. Finally, theories concerning the dominance of one type of feedback over another might be expanded to include considerations of "critical age" and type of feedback relationships. For example, it is quite plausible that the type of feedback important during a speech acquisition stage of development is different from that which controls already acquired and stabilized speech activities. Failures to account for this view may help explain the poor correlations that are often reported between sensory skill capacities and speech proficiency. In other words, an adult's failure or excellence of performance on a sensory task does not yield much insight into the sensory level at which the subject functioned during an earlier, and perhaps even more cirtical, time.

FUTURE RESEARCH DIRECTIONS

Perhaps the most basic and critical question that remains to be resolved deals with the exact nature and relative importance of tactile and kinesthetic feedback in the development and maintenance of normal speech and in the rehabilitation of disordered speech.

It is unrealistic and perhaps unwarranted to expect the investigator who studies sensory phenomena in their totality and the neurophysiologist who becomes involved with sensation at a cellular level to view oral sensation and perception from the same perspective. As Jerge (1967) has pointed out, however, eventually workers studying the problem at those different levels must reconcile their data, and observations of all types must intertwine to form a complete and accurate picture.

Jerge (1967) further notes that since research in sensory physiology has demonstrated that the central nervous system is capable of modifying, even at the level of the primary receptor, the quality of information admitted for subsequent transmission, the role of receptor inhibition in the trigeminal system must be clarified. Also, the importance of the reticular formation in oral sensation should be stressed, as it is well known that it has a profound influence on transmission through sensory relay nuclei. Attempts also should be made to specify the actual neurophysiological mechanism by which observed sensory events take place.

Inasmuch as sensory networks are capable of undergoing and, in fact, do undergo structural changes in response to long-term changes in level or quality of impinging stimuli, and since sensation and perception as phenomena have a learning and experience component, the plasticity of the nervous system almost certainly will become a promising subject of investigation by sensory physiologists and rehabilitation specialists in the future.

The factors of retention, anatomical maturation, and motor development that are thought to be critical for the development of oral discrimination abilities also are said to underlie the processes of speech. It is hoped that in the future investigators will ask whether sensory discrimination abilities and speech development exist in a cause-effect relationship, or whether they both are related to more general factors such as neurological maturation or perceptual skill development. If the cause-effect hypothesis is accepted, oral sensory disturbances can be considered as a new etiologic entity for defects of articulation, and ways of compensating for such disturbed input channels should be sought.

In such future work we must explore rehabilitation approaches that further develop prosthetic devices such as those described by Grossman and Bosma (1963) which may assist patients in compensating for sensory deficits. Also, efforts must be directed at identifying pharmacologic agents that might promote the discrimination process. If, as noted earlier, sensation and perception have a learning and experiential foundation, then Magoun's (1967) comments on recent studies of the facilitation of learning by such neuronal stimulants as caffeine, strychnine, and picrotoxin may be relevant to persons demonstrating speech disorders etiologically based in sensory-system dysfunctioning.

A number of questions about the nature of speech therapy for persons with oral sensory disturbances must be investigated also. Should training be aimed at developing the use of input channels for speech monitoring that might serve in lieu of the disturbed channel (Chase, 1967), or should the tactile-kinesthetic channel be used regardless of its level of functioning? If it can be demonstrated that speech proficiency and oral discrimination ability are interdependent skills, then the value of teaching oral discrimination tasks as a requisite (or prerequisite) for conventional therapy should be explored. An attempt at this form of therapy has been reported by Shelton and his associates (1970). Their efforts to teach discrimination of palatal movements have not at all been encouraging but, at this stage of experimentation, should not dissuade future research efforts in this general direction.

The tasks we use to measure oral discrimination abilities also must be studied further. Such research must be directed toward the delineation of types and levels of sensory functioning called for by tasks of oral form recognition and discrimination. It is only when these questions can be answered that an understanding of the significance of this deficit in pathological speakers can be attained. In this respect it should be noted that some excellent suggestions for research have been proposed (Shelton, Arndt, and Hetherington, 1967).

With reference to better understanding the effects on speech of disturbed oral sensation, techniques of physiologic articulatory phonetics should be employed to specify further the exact nature of articulatory changes which occur. Such techniques might include pressure and flow measures, cineradiographic and motion picture observations, and electromyography. To illustrate further the need for technique development we need only look at the limitations placed upon the interpretation of nerve-block experiment results by our inability to adequately test the potential motor effects of anesthetizing drugs. Elsewhere in this *Report,* Harris ("Physiological Measures of Speech Movements: EMG and Fiberoptic Studies") notes that a subject studied in her laboratory by EMG procedures demonstrated mylohyoid paralysis after a nerve-block injection. While EMG results of the type reported by Harris are important in studying motor functioning, they do not provide a clear method for determining whether the atypical EMG pattern is truly reflective of a motor system paralysis or whether the patient exhibits abnormal motor activity (as demonstrated in EMG recordings) because of a sensory deficit. Although this problem may be dealt with by direct neural stimulation techniques, such approaches have not found common use in studies of the speech musculature. Future research must develop tests that will allow for the clear determination of the level at which the speech system fails in different types of communicative disorders.

By way of summary, the ability to differentiate between normal-speaking and speech-disordered persons on the basis of information gained through sensory testing is significant both from an applied and a theoretic point of view. Evidence supporting the view that normal speech is reflected in orosensory functioning argues for the acceptance of a speech-production model that incorporates some servomechanical features, and for a variety of therapeutic practices that are compatible with such a model. Any theorizing about the processes of speech and language development and their maintenance must take into account the sensory mechanisms underlying articulatory activity (Ringel et al., 1970).

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AERODYNAMIC AND ULTRASONIC ASSESSMENT TECHNIQUES IN SPEECH-DENTOFACIAL RESEARCH

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Techniques used in the assessment or quantification of physiologic functions typically follow a fairly consistent maturational pattern. Given some need, specific or general, a technique either is devised or borrowed from some other application or discipline. The technique first is subjected to laboratory or clinical tests in an attempt to establish its validity, reliability, and practicality. If necessary, modifications are made in the technique. Ideally, the test and modification stage never ends, but continues throughout the functional life of the technique. However, when one or more investigators demonstrate that the technique is a valid, reliable, and practical assessor of some physiologic function, the testing stage gives way in primacy to an application stage in which the technique is applied in the clinic, used in the laboratory to obtain normative data, or used to test hypotheses. The overlap in these stages is great. Studies that are concerned primarily with the development of a technique often provide some descriptive data or advance tentative hypotheses as well. Nevertheless, such a maturational pattern provides a useful means for considering assessment techniques such as those described in this paper.

AERODYNAMIC ASSESSMENT TECHNIQUES

The need for the development of aerodynamic assessment techniques can be stated quite clearly. In the first place, speakers with anomalies of the dentofacial complex (such as cleft palate) typically have difficulty producing those speech sounds that require the generation of controlled egressive airflow and the maintenance of air pressure greater than atmospheric. Therefore, the precise assessment of airflow and pressure patterns in normal speech production, and a description of the patterns of deviant speech, becomes essential. In addition, data related to orifice areas (for example, the velopharyngeal orifice area and areas of oral constriction) and the resistance to airflow (for example, nasal resistance) clearly are important in the description of normal and abnormal speech mechanisms, as well as in diagnostic and prognostic evaluations of abnormal speakers. Hydraulic principles provide such area and resistance data from air pressure and airflow information (Warren and DuBois, 1964; Hixon, 1966; Warren and Ryon, 1967; Rothenberg, 1968; Lubker, 1969) without subjecting the patient to discomfort or radiation.

More generally, and perhaps more importantly, knowledge of the aerodynamic characteristics of speech production is requisite to a complete understanding of the complex process of speech, providing data to aid in the development and testing of theoretical models of speech production.

Thus, a clear need for aerodynamic data exists. This was recognized some time ago, and a good deal of effort has been expended to develop and refine techniques suitable for obtaining such data. Many investigators have contributed and are contributing to this testing and development.

Stetson and his coworkers (Stetson, 1951) and Black (1950) acted as catalysts to later efforts. Hardy and his colleagues at Iowa (Hardy, 1961, 1965, 1967), Lubker and Moll (1965), Hardy and Edmonds (1968), Warren at North Carolina (Warren and DuBois, 1964; Warren and Devereux, 1966), and Subtelny and her associates at Rochester (Subtelny, Worth, and Sakuda, 1966), as well as many others, have led in the development of the aerodynamic techniques in use today.

As Hardy (1965) pointed out, aerodynamic instrumentation typically includes several basic components: a sensing device, a transducer, a signal conditioner, and a recording system.

AIRFLOWS

Two systems presently are generally used to measure airflow rates occurring during speech. The difference between the systems is due primarily to the choice of sensing device.

The sensing element most commonly used to measure airflow is the pneumotachograph, or Fleisch tube, as it is sometimes called in honor of the developer of the principle. This system relies upon the physical law that, as air flows across a resistance, the air pressure drop across that resistance bears a linear relation to the rate of airflow. The pressure drop, or differential, is applied to a pressure transducer, where it is converted to an electrical signal, which is then amplified and recorded on the instrument of choice (for example, FM tape recorder, ink-writer, light galvanometer). The advantages of the pneumotachograph system are several: (1) it is well established as a valid, reliable, and linear technique for measuring airflow rates (Silverman and Whittenberger, 1950; Fry et al., 1957); (2) it is calibrated easily, and once calibrated, very stable; (3) its design and principle are simple, making it inexpensive and easy to maintain; and (4) it detects and differentiates between egressive and ingressive flow (if it did not do so, ingressive flow during speech would be recorded as egressive, thereby introducing a potentially large and uncontrollable source of error). The primary disadvantage of the pneumotachograph is that it requires the use of some sort of face mask (Comroe, 1950) to trap or channel the flow of air through the device. A mask over the face places certain restrictions on articulatory movements. Lubker and Moll (1965) have suggested that these restrictions primarily are limited to lip and jaw movements and, even then, are highly phoneme-dependent. It is probable that face masks need not fit as tight as those used by Lubker and Moll, so that the effects of the mask on articulation may be even less than they reported. Furthermore, methods for trapping airflow which are less restrictive than the more conventional face masks have been reported (Klatt, Stevens, and Mead, 1968). In my observations, face mask effects have never been severe enough to offset the advantages of the pneumotachograph system, and continued experience has strengthened that judgment (see also Hardy, 1965).

The second airflow measuring technique in fairly general use, the warm-wire anemometer, involves a heated wire as the airflow sensing element. The basic principle involves the cooling effect of a flow of air on a heated wire through which an electric current is flowing. As the wire is cooled, its resistance to current flow is altered in a systematic manner. The variations in the electrical signal passing through the heated wire, when amplified, recorded, and calibrated, provide a record of flow rate. The primary advantage to this system is that there is no need for a face mask to channel the flow of air. Although some applications have been made where a single heated wire is placed in a tube very similar to a pneumotachograph which is then attached to a face mask (Quigley et al., 1964; Van Hattum and Worth, 1967), more recent use has involved the suspension of a series of wires in front of and close to the oral or nasal ports, without a mask (Subtelny, Worth, and Sakuda, 1966; Subtelny et al., 1969). The warm wire, or wires, must be arranged rather close to the subject's mouth and their distance must be constant throughout the experiment, so that either the subject's head movements need to be restricted or the apparatus must be attached directly to his face, or both. Clearly some restrictions to articulatory movements exist with the warm-wire anemometer system, although a direct comparison to the restrictions imposed by the pneumotachograph mask system cannot be made due to a lack of experimental data. In addition to not providing a clear advantage over the pneumotachograph with respect to restricting articulation, several other disadvantages of the warm-wire anemometer may be cited: (1) the warm-wire system has poorer linearity and frequency response than does the pneumotachograph; (2) the warm-wire system does not allow the experimenter to differentiate between egressive and ingressive flows, thereby introducing an uncontrolled source of error; (3) the warm-wire system is more difficult to calibrate than is the pneumotachograph; and (4) the number of wires needed and their most efficient location probably varies for different phone types, and perhaps for different speakers. A more detailed discussion of the disadvantages of the warm-wire system may be found in van den Berg (1962), Hardy (1965), and Klatt, Stevens, and Mead (1968).

There is a third airflow measuring system that is not commonly used. This system is quite different from the pneumotachograph and warm-wire anemometer, in that it does not measure airflow rate directly. Air volume is measured via a body plethysmograph and spirometer, and average flow rate is calculated from the volume. Mead (1960), for example, has reported using this technique. But, in a later article Klatt, Stevens, and Mead (1968) stated that the technique does not have a frequency response adequate for general use in speech research.

AIR PRESSURES

Three basic systems generally are used to study air pressures. The system most commonly used involves placing a tube into the cavity (oral, nasal, or subglottal). The tube is attached directly to a transducer, amplifier, and recording system. The characteristics of the tube itself are quite important. To prevent stagnation pressure artifacts, the tube either should be sealed at the end with small holes drilled in the sides near the sealed end, or it must be oriented so that the end is perpendicular to the flow of air. Furthermore, it is generally accepted that frequency response will be adversely affected if the tube is overly long or has too small a diameter (Hardy, 1965). However, it should be recognized that the main effect of decreasing the diameter of the tube is to damp resonance peaks and to cut off the high frequency response. Thus, at least in theory, small diameter tubes would have a flat frequency response with high frequency cut off being dependent on the actual tube diameter. Obviously, there is an optimal diameter, being neither too large nor too small. In addition to possible pressure artifacts such as those outlined above, insertion of the tube into the oral cavity may cause the subject some difficulty with articulation, especially with movements of the tongue. Much of the potential articulatory disruption can be avoided by passing the tube around the maxillary arch and behind the upper third molar or by using a transnasal approach. In studies where tongue movement is minimal or unimportant (Lubker and Parris, 1970), the tube simply may be placed directly between the lips and into the center of the oral cavity. When properly applied, the tube system provides a valid, reliable, and practical technique for evaluating pressures in the vocal tract.

A second pressure measuring system attempts to circumvent the potential disadvantages of the tube system by placing a miniature pressure transducer directly into the cavity, thus eliminating the tube altogether (Subtelny, Worth, and Sakuda, 1966; Koike and Perkins, 1968). Although it seems unlikely that a transducer and its associated wires placed in the oral cavity would offer any advantages over a tube system with respect to impeding articulatory movements, it cannot be argued that any pressure artifacts introduced by a tube would be eliminated if the tube were eliminated. More accurately, the need to account for such artifacts would be eliminated. However advantageous this might be, many miniature pressure transducers presently available have at least one fault in common that is potentially quite serious, namely a rather marked temperature sensitivity (see also Hardy, 1965, 1967). Under controlled conditions such as a slow, steady rise in temperature, the base line of such a transducer's output shifts in a similar slow, steady manner. Temperature that varied in a relatively rapid and erratic manner would be expected to have variable effects on the transducer's output. Examination of the figures in a recent publication by Koike and Perkins (1968) suggests that not all miniature pressure transducers are so affected by temperature changes. Thus, as advances in the field of biological electronics continue to be made, miniature pressure transducers may well have an important contribution to make in the study of speech aerodynamics. At present, however, the tube-transducer system seems to be the most useful.

The third type of pressure measuring system is the oral manometer. The oral manometer is intended to answer a need for a simple, economical tool to assess a speaker's ability to generate intraoral pressure under a variety of blowing and sucking conditions. Such a system does not measure intraoral pressure during connected speech and, in a sense, it is an aerostatic rather than an aerodynamic system. If such techniques are useful at all, it is primarily insofar as they are able to predict a speaker's speech proficiency, although knowledge of velopharyngeal function during nonspeech activities may sometimes be valuable. Lubker and Schweiger (1969) obtained a correlation of 0.72 between breath pressure ratios from oral manometer scores and Iowa Pressure Articulation Test Scores, and a correlation of 0.60 between breath pressure ratios and judgments of velopharyngeal adequacy for prosthetically managed cleft-palate speakers. Similar correlations have also been reported by Barnes and Morris (1967). While Morris and his associates at Iowa (Morris, 1966; Pitzner and Morris, 1966; Barnes and Morris, 1967) have argued strongly for the clinical validity of the oral manometer, the individual experimenter must decide whether correlations such as those reported above are high enough to warrant using this pressure measuring technique in a given clinical or laboratory situation.

The measurement of subglottal air pressure presents some unique features and therefore will be given special consideration in this report. At least three separate techniques have been applied to the measurement of subglottal pressure. In one, a large-bore hypodermic needle (18 gauge) is inserted between the second and third tracheal rings directly into the lumen of the trachea, just below the glottis. The hub of the needle is then attached either directly to a transducer or to the transducer via a short length of tubing (Kunze, 1964; Netsell, 1969a, b). A second method involves placing a small balloon into the esophagus directly behind the trachea (Ladefoged, 1961; Lieberman, 1968). The assumption behind this second method is that pressure changes in the trachea will be recorded by the esophageal balloon, which is lying in intimate contact with the posterior wall of the trachea. There is considerable controversy over the validity of this second technique as compared to the direct, or tracheal puncture, technique (Kunze, 1964; Ladefoged, 1964; Lieberman, 1968). It appears, however, that the validity of the esophageal balloon method is contingent upon a number of factors, most importantly lung volume, which are difficult to specify at any given instant during speech production. A third method, that is also termed "direct," has been suggested by van den Berg (1956), in which a tube is placed directly into the trachea by passing it through the glottis from above. More recently Koike and Perkins (1968) have used an approach similar to van den Berg's by placing a miniature transducer directly into the trachea. At the present time, the direct tracheal puncture method appears to be the most valid and practical technique for measuring subglottal pressures during connected speech.

In my judgment the pneumotachograph transducer and tube transducer systems possess basic advantages over other systems for the measurement of airflow and pressure during speech production. It is most emphatically not asserted that this will always be the case. It is, for example, altogether possible, or perhaps even probable, that transducers even smaller than those presently available will be developed that will more than meet our needs. We must remain alert to the development of such equipment and be willing to try it, or to listen to those who have tried it.

The development of telemetry may also have important benefits for aerodynamics research. As an example, such systems already are small enough to be clipped to the buccal side of the molars without disrupting articulation. When coupled with an appropriately responding miniature pressure transducer, the subject would have no tubes or wires leading from the oral cavity and would have complete freedom to move about. Again, we must not become so dependent on our present techniques that we are unwilling to consider new and possibly better ones.

Further, we are, indeed, living in the age of the computer. The data with which we are concerned is almost tailor-made for computer control and analysis. Little has been said in this report about data recording systems. At present, many researchers consider the epitome of data recording to be the multichannel FM tape recorder. With such a system, a number of valuable steps can be accomplished, for example, the recording of numerous simultaneously sampled variables (aerodynamic or others), computer analysis of the tape-recorded material, and step-down playback into a paper-writer to allow for an expanded time scale. The computer is able to accomplish the tasks of data reduction and analysis with far greater speed and accuracy than can a human observer. In fact, it may well become common practice to dispense with the tape recorder altogether and use the computer as an on-line control and analysis device. It also should be noted that the ability to sample a number of physiological variables simultaneously (for example, several aerodynamic parameters, several electromyographic signals, and an acoustic signal) provides the experimenter with far greater flexibility in his attempts to devise critical tests of hypotheses.

Finally, the manner in which the aerodynamic data has been measured and will be measured should be considered. It has been relatively common practice to use peak pressure or flow as the criterion variable (Subtelny, Worth, and Sakuda, 1966; Arkebauer, Hixon, and Hardy, 1967; Lubker and Parris, 1970). However a number of authors have suggested that other criterion variables might be more appropriate. Lisker (1965), Malécot (1966), and Lubker and Parris (1970), for example, presented convincing evidence that the time integral of the pressure or flow curves may provide more valid differentiation between two pressures or flow curves than does peak amplitude. Various duration measures also have been proposed (Lisker, 1965). When tabulated by hand, such data are far more difficult and time-consuming to obtain than are peak amplitudes. However, computer analysis of the data will permit us to extend our criterion variables to allow more complete evaluation of the aerodynamic data available.

The aerodynamic techniques described here have really changed very little since Hardy discussed them (1965). This observation suggests that, since 1965, we have moved more into the application stage of aerodynamic measurement technique. Indeed, only a cursory review of the literature tends to corroborate this suggestion.

APPLICATION OF AERODYNAMIC TECHNIQUES

Applications of aerodynamic techniques have, in fact, been so extensive that a comprehensive review is beyond the scope of this paper. Perhaps the most economical way to approach such a review is not by citing specific research, most of which can be found in the accompanying bibliography, but rather by viewing broad areas of application.

Nasal Pressure. Although measures of nasal pressure alone once enjoyed a degree of popularity (Young, 1953; Hess and McDonald, 1960), they are seldom used in contemporary aerodynamic research, except in conjunction with measures of oral pressure to obtain the air pressure drop across the velopharyngeal orifice. Accordingly, consideration of these measures will be withheld until the measurement of oral pressure is discussed.

Nasal Flow. A number of researchers (Quigley et al., 1963; Quigley et al., 1964; Quigley, 1967) have suggested that nasal airflow provides an index of velopharyngeal adequacy. Their position, briefly stated, is that the greater the rate of nasal airflow, the greater the velopharyngeal opening, thus allowing a quantitative measure of velopharyngeal adequacy. Other investigators, however, have demonstrated that nasal airflow rate alone is not a good predictor of velopharyngeal patency (Lubker and Moll, 1965; Warren, 1967; Lubker and Schweiger, 1969). They purport that a number of factors in addition to velopharyngeal patency, namely oral port constriction, nasal resistance, and vocal effort, influence nasal airflow and that these factors must be taken into account. Further, there are data indicating that nasal airflow can occur in the presence of a closed velopharyngeal port, perhaps due to the rising soft palate, which decreases the size of the nasal cavity, thereby forcing air from it (Lubker and Moll, 1965). Recent research indicates that nasal airflow during nonnasal English phoneme production does not necessarily imply defective speech or faulty velopharyngeal function (Lubker and Moll, 1965; Van Hattum and Worth, 1967; Lubker and Schweiger, 1969; Subtelny et al., 1969; Lubker, in press). Listeners apparently are able to tolerate some, as yet unspecified, level of nasal airflow before labeling the speech as abnormal. More precisely, nasal airflow rate must reach a certain level before turbulence in the nasal cavities becomes great enough for listeners to react adversely to it. In any case, the evidence presently available indicates that nasal airflow rate alone does not provide a very promising diagnostic or prognostic tool with respect to velopharyngeal patency.

Nasal airflow data is of considerable value when combined with other data, such as the pressure drop across the velopharyngeal orifice, making it possible through the use of hydraulic principles to calculate the area of the velopharyngeal orifice, as well as the nasal and velopharyngeal resistances to airflow, during connected speech. The use of hydraulic principles in speech research was discussed at least as early as 1956 by Heinz (1956) and by Fant (1960). Hydraulic principles have been applied most extensively by Warren (for example, Warren and DuBois, 1964), and to a lesser extent by other investigators, such as Hixon (1966). Such data are of obvious diagnostic and prognostic value, not to mention their value in our attempts to understand normal speech production.

Subglottal Pressure. Subglottal pressures have received a good deal of attention from speech scientists. Emphasis has been primarily on the relations between subglottal pressure variations and such parameters as vocal intensity, pitch, and stress (van den Berg, 1956, 1957; van den Berg, Zantema, and Doornenbal, 1957; Ladefoged and McKinney, 1963; Isshiki, 1964; Mead, Bouhuys, and Proctor, 1968; Lieberman, Knudson, and Mead, 1969; Netsell, 1969a). However, until rather recently subglottal pressures were considered to be irrelevant to the dentofacial complex. Only recently has it been recognized that glottal activity and subglottal pressures are importantly related to supraglottal aerodynamic events (Rothenberg, 1968; Warren and Wood, 1969; Netsell, 1969b). Precisely what these relationships are, and the extent to which they are valid and significant, remains a source of controversy and a fruitful research area.

Oral Airflow and Intraoral Air Pressure. These two parameters, particularly intraoral air pressure, have been the impetus for a great deal of aerodynamic research in speech. This is the case because the development of intraoral pressure and its subsequent release as airflow is crucial to normal speech production, and the ability to control those air pressures and flows so often is lacking in speakers with dentofacial anomalies. It is not surprising, then, that there is a large body of oral pressure and airflow data, separately as well as in combination with such parameters as nasal air pressure. As a result, we are able to make a whole host of carefully qualified statements and pose a number of hotly contested controversies. For example: (1) when position, effort level, and rate of utterance are held constant, voiceless consonants are generally produced with greater intraoral air pressure and oral airflow than are their voiced cognates; (2) voiceless plosives usually demonstrate greater intraoral pressure than voiceless fricatives, whereas voiced fricatives usually have greater intraoral pressure than voiced plosives; and (3) some investigators contend that intraoral pressure differences between voiced and voiceless sounds are due to some aspect of glottal activity, while others contend that the differences primarily are due to vocal effort.

It is not unlikely that the application of aerodynamic techniques has proceeded at such a rapid pace that we find ourselves with a maze of data, a number of controversies, the import of which no one is terribly sure, and little more. To quote John Platt (1964):

> Surveys, taxonomy, design of equipment, systematic measurements and tables, theoretical computations—all have their proper and honored place, provided they are parts of a chain of precise induction of how nature works. Unfortunately, all too often they become ends in themselves, mere time-serving from the point of view of real scientific advance. We speak piously of taking measurements and making small studies that will "add another brick to the temple of science." Most such bricks just lie around the brickyard.

Platt could well have been speaking directly to the present state of research in speech aerodynamics. This is not to say that our efforts to obtain descriptive data are in error, or even that such efforts should end. Indeed, we are still in need of descriptive aerodynamic data in a great many facets of our research. Rather, we may need to (1) reevaluate precisely what kinds of data are most useful, (2) consider how we can most efficiently and effectively apply that data to the development and testing of crucial hypotheses, and (3) concentrate on the development of hypotheses. Of course, some excellent efforts are already being made along these lines, such as Rothenberg's (1968) consideration of breath stream dynamics, and Peterson and Shoup's (1966) inclusion of aerodynamic concepts and parameters in their physiological model. Unfortunately, examples such as these are rare.

Aerodynamic assessment techniques provide us with the means for obtaining important and useful information about normal and abnormal speech production. These techniques have allowed us to obtain a vast amount of data—to follow Platt, a large number of bricks for the temple of science. There is clearly much more that needs to be done. However, it may be that it is time to evaluate just what is being done with the bricks that we have built and are proposing to build. Are our data really being used, or are they even useful? Perhaps it is time to begin the development and testing of broader and more far-reaching hypotheses and apply, if possible, our research data to the clinic to see if they really are useful.

FUTURE APPLICATION OF AERODYNAMIC TECHNIQUES

It is presumptuous for one individual to dictate specific research directions to members of his research-academic community. Therefore, the following statements should be taken only as general suggestions. Some are clearly more restrictive in scope than others.

Given control of such variables as nasal resistance and phone types, it would be valuable to know what level of nasal airflow caused audible turbulence to develop in the nasal cavities. More specifically, a precise understanding of the relationships among nasal flow, turbulence, nasal resistance, phone type, and so on, would be most useful in the diagnosis, prognosis, and treatment of individuals with velopharyngeal dysfunction. Such information would also be of interest in the clarification of normal speech processes.

The extent and the import of relationships between glottal activity and subglottal pressure and supraglottal activities and pressures need further description and clarification.

Aerodynamic data can contribute to an understanding of coarticulation and segmentation—that is, they can assist our attempts to elucidate the dynamic characteristics of speech production. As Rothenberg (1968) has pointed out, "air flow energy" in most cases generates the "acoustic energy of speech." If this is true, then breath stream dynamics logically must be included in many, if not all, of our attempts at modeling speech production. Consider, for example, the problem of segmentation. Daniloff and Moll (1968) have suggested that a consonant actually begins "in an articulatory sense" when the articulator begins its movement toward the consonant—that is, consonant articulation includes the VC transition. It is perhaps more likely that a consonant actually begins, in an articulatory sense, when the movement of the articulators first alters the flow and pressure parameters typically used to define the consonants. Thus, when coupled with electromyographic or cinefluorographic techniques, aerodynamics may offer a very practical aid to the problem of segmentation. Aerodynamic-coarticulation data also may be of some value. For example, it is generally agreed that an individual with faulty velopharyngeal function will have more difficulty producing the word *pad* than *bad*, due to the greater pressure requirements for the initial consonant. Will that same speaker also have more difficulty with the initial consonant in *bat* than with *bad*, and, if so, is this due to coarticulatory effects of the increased pressure requirements for the final consonant? A related question is: are the words *bad* and *bat* made up of a series of basic units, that is, phonemes, or are they basic units themselves, that is, "articulatory syllables" (Kozhevnikov and Chistovich, 1965)? It seems clear, then, that aerodynamic data used in conjunction with other observational techniques can aid in the clarification of the concepts of coarticulation and segmentation, which are so important to the understanding of speech production as a dynamic mechanism.

ULTRASONIC DIAGNOSTIC TECHNIQUES

The maturational pattern applied to aerodynamics also is useful when applied to diagnostic ultrasound as it has been used in speech research. Diagnostic ultrasound techniques have been in use for some time in a wide variety of physiologic assessment applications (see Grossman, Holmes, Joyner, and Purnell, 1966). However, only recently have these techniques been applied to speech research. The use of ultrasound in speech research has been pioneered by Minifie, Kelsey, and others at the University of Wisconsin. In fact, virtually all ultrasound-speech data presently in print comes from that institution (Minifie, Kelsey, and Hixon, 1968; Beach and Kelsey, 1969; Kelsey, Hixon, and Minifie, 1969; Kelsey, Minifie, and Hixon, 1969; Kelsey, Woodhouse, and Minifie, 1969). Some European workers also have experimented with the techniques, but their results were inconclusive, precluding publication. Although the amount of data available is limited, the concept has attracted enough attention to warrant consideration at this conference.

The proponents of ultrasound suggest that it is of value in the investigation of normal and abnormal speech production since it does not require the insertion of wires or tubes into the vocal tract nor does it involve the use of radiation. No one could take issue with this, assuming that (1) the proposed technique causes the subject no more danger or discomfort than the technique it replaces; (2) the insertion of tubes and wires into the oral cavity results in speech that is significantly distorted from the normal; (3) the radiation levels presently in use in radiographic speech research are harmful or dangerous; and (4) the proposed technique provides at least as good and as much information as those it supplants. The first of these assumptions apparently is correct. The validity of the second and third assumptions is open to question. The fourth assumption will be considered in more detail subsequently.

Basically, the ultrasonic technique involves "bouncing" high-frequency pulsed sound waves off impedance-mismatched interfaces. The amount of sound energy reflected at an interface depends upon the degree of impedance mismatch and the angle at which the sound wave strikes the interface. Maximum reflection occurs at a tissue-air interface (for example, pharyngeal wall-pharynx tube), and normal incidence angle. The time taken for a reflected sound (echo) to return to the transducer which generated it provides an accurate measure of transducer-interface distance. The basic technique can be modified in several ways (see Kelsey, Minifie, and Hixon, 1969) so that a moving interface can be recorded with considerable accuracy.

The Wisconsin group also has made use of the Doppler ultrasonic principle (Minifie, Kelsey, and Hixon, 1968; Beach and Kelsey, 1969), in which a continuous rather than a pulsed sound wave is directed at a moving structure. The frequency shift that is described by the Doppler principle is detected by beating the reflected signal against the transmitted signal to obtain a difference signal, or Doppler frequency. The velocity and displacement of the moving structure can be determined from the difference signal, but its direction of movement cannot. A more complete description of the Doppler ultrasonic principle is provided by Minifie, Kelsey, and Hixon (1968).

From the data available in the literature cited, it is possible to make a series of statements, some positive and some negative, concerning the technique of diagnostic ultrasound in speech research. First, some positive aspects: (1) the technique is apparently safe and painless, offering no discomfort to the subject. Frequency levels used in diagnostic ultrasound are far below those used to destroy tissue. (2) The technique works. That is, interface reflections do, indeed, occur. Such reflections are especially marked from the lateral pharyngeal wall interface. (3) The technique is reliable. For 20 measures taken over a two-month period on one subject, the standard error for static lateral pharyngeal wall distance was only 1.8 mm. (4) Vertical resolution seems more than adequate—approximately 1.0 mm. This resolution is limited by the wavelength of the sound beam. Higher wavelengths result in better vertical resolution, but poorer depth penetration.

On the negative side: (1) lateral resolution is not so good. It is limited by the beam width and is usually on the order of one cm. In addition, this provides quite a small visual field. (2) The angle of reflection is important, and an incident angle of only 10 degrees will cause most of the energy to be reflected away from the transducer. Therefore, the transducer must be held at perfect right angles to the structure or structures in question. If those structures are curved, the difficulties presented are even greater. (3) To interpret the source of reflections, a rather considerable knowledge of the normal range of anatomical relationships is required. This requirement presents particular difficulties when dealing with the physiologically abnormal or altered case, when such knowledge is at best problematical.

Thus, diagnostic ultrasound can be used to obtain certain information about the shape and movement of the vocal tract, or at least parts of it. However, this technique requires a great deal of precision and, even then, interpretation of the obtained data rests on the assumption that the anatomical relationships are, indeed, as described in standard texts. Interpretation would be even more tentative when dealing with anatomical relationships not described by texts, that is, the physiologically abnormal.

Of course, precision is necessary with any technique, and data interpretation is seldom clear-cut. Thus, the real issue is: does this technique provide us with data not easily and reliably obtained with methods already available to us? To quote Kelsey, Hixon, and Minifie (1969): "Ultimately the choice of observational techniques should reflect an attempt to derive the best possible information with the least possible risk to the subject." The next logical step, then, is to view this technique in its application stage in order to determine whether it provides us with information that is unique or better than that provided by other techniques.

To date, pulsed ultrasound has been applied solely to the study of lateral pharyngeal wall movements, and Doppler ultrasound has been used to observe vocal fold movements. However, the latter application has been discredited by Beach and Kelsey (1969), who state that "it seems unlikely that the proposed Doppler technique can be used for determining the instantaneous velocity and displacement of human folds during phonation." The difficulty seems to be that the curved surfaces of the folds provide multiple reflections of the sound beam, many with non-normal incident angles, and that the folds change shape and velocity as they vibrate.

At present there appears to be but one application for the technique, that of specifying lateral pharyngeal wall movements. And it may be that this is the only application, at least for the near future. It would, for example, be difficult to observe tongue or soft palate movements, since tissue-air interfaces often would block passage of the sound beam to the structure being studied. Further, the multiplicity of structures and their rapidly changing relationships above the level of examination presently used would be expected to make data interpretation even more difficult. If this is true, then application of the technique to lateral pharyngeal wall movements around obturators and pharyngeal flaps may prove difficult at best. On the other hand, it is becoming clear that the pharynx probably functions as an articulator of sorts during speech production. Ultrasound probably is the best existing method for evaluation of movements of the lateral walls of this "articulator." Although presently somewhat limited in its application, diagnostic ultrasound may have some future application in speech research. It thus remains an intriguing technique which should continue to be tested and examined with some care.

CONCLUDING COMMENTS

Peter MacNeilage (in press) has pointed out that the problem of serial order in behavior was originally expressed by Lashley (1951), who posed the question as to what mechanisms are used to produce smooth, temporally ordered sequences of action. MacNeilage then went on to attempt to "provide an account of those aspects of the serial ordering process most directly responsible for the sequencing of the movements (and therefore the sounds) of language." Apparently, attempts at describing the sequencing movements, whether normal or abnormal movements, are crucial, indeed. The development of hypotheses relevant to the mechanisms responsible for the sequencing, and hypotheses relevant to the effects of breakdowns in those mechanisms, is really what we are all concerned with.

Aerodynamic techniques provide us with a means for aiding in the development and testing of such hypotheses, as well as in the evaluation of mechanisms and breakdowns thereof. To the extent that we allow this technique to live up to its potential, it should continue to serve us well.

Ultrasonic techniques, as they are presently available, appear to provide us with a more limited means for testing hypotheses and describing mechanisms. Their value in describing certain structures, namely lateral pharyngeal walls, is not to be denied and should, in fact, be encouraged.

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ACOUSTIC AND ANALOGUE STUDIES

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For numerous reasons, researchers today are interested in acoustical studies of the speech signal. While it will be impossible to cover all of these, it will be instructive to survey briefly the variety of such interests so that the reader may understand how the topic has been limited for the purposes of this paper.

In a general way, at least, persons who have a particular interest in the acoustics of speech may be classified into three groups. The first group comprises those who are directly interested in studying the physical properties of speech for their own sake. Most of the persons in this group have a primary concern with such communication engineering problems as more efficient transmission of speech signals, storage of speech signals and their retrieval at times and places remote from their origin, automatic transformation (or recoding) of speech signals into forms that will facilitate communication between man and machines, and so on.

The primary interest of the second group is in the processes of speech production. Persons in this group have two reasons for being concerned with the physical characteristics of the speech signal. First, they must be able to relate the physiological events of speech production to the acoustic signals that are the end product of those physiological processes. Second, they may be interested in the acoustical analysis of speech because, by analyzing the output of the speech production processes, they hope to gain insights into physiological events which are themselves not readily accessible for direct observation.

The third group consists of students and investigators whose principal interest centers on the processes of speech perception. They are interested in the physical characteristics of speech because the speech signal constitutes the stimulus of the stimulus-response chain that they seek to understand. To describe the nature of this chain they must be able to specify the characteristics of the acoustic stimulus with reasonable precision. Moreover, to conduct relevant experiments, they must be able to devise means of controlling the variations of the physical stimulus with reasonable precision.

Obviously, these groups and their interests are not as separable and independent as the foregoing discussion suggests. Quite typically, researchers will have interests of such breadth as to cut across more than one of these classifications, and the research projects of the several groups are more often than not complementary. However, because space limitations make it necessary to be selective, and because the focus of this *Report* is in large part physiological, I will stress those facets of the acoustic analysis and analogue studies of speech that provide a basis for better understanding of the physiological processes of speech production. Even with this limitation, it will be impossible to review the accumulation of research literature in detail. Consequently, major attention will be limited to research techniques, with secondary emphasis on summarizing current knowledge about the acoustic characteristics of speech. The assumption is that information about available research techniques will be of primary importance for persons planning future research concerned with speech and the dentofacial complex.

SPEECH ANALYSIS TECHNIQUES

Figure 1 is an oscillogram showing the instantaneous sound pressure variations that constitute the acoustic signal of a short sentence. The figure will serve to demonstrate several relevant points.

First, the wave forms of speech are highly complex. For example, the wave forms in some parts of Figure 1 appear to be relatively periodic; other parts show no periodicity. The relatively periodic portions, in which a given pattern or wave form is more or less regularly repeated a number of times, correspond to the segments of speech in which the vocal-fold vibration constitutes the principal source of acoustic energy. Vowels are speech segments of this kind, as are certain consonants, such as the nasal consonants. For sounds of this type the breath stream that acts as the sound carrier is relatively unimpeded as it passes outward through the mouth or nasal cavities. The completely aperiodic portions correspond to speech segments during which the vocal folds do not vibrate and the generation of sound is due either to (1) forcing air through a small constriction formed between articulatory structures, such as the lips, tongue, teeth, and palate, so that turbulence is created in the breath stream, or (2) an explosive release of air that has been impounded by a complete occlusion of the vocal tract at some point, for example, by contact between the lips, or between the tongue and the gum ridge. In either case, the resulting sound has no periodically repeated pattern of the kind that results from a regularly vibrating source, such as the vocal folds. The result is aperiodic noise. Examples of such speech segments are the voiceless fricative consonants, such as /s/ and /f/, and the release phase of the voiceless stops /p/, /t/, and /k/. Other parts of Figure 1 correspond to segments in which both types of sound sources are effective—for example, the voiced fricatives, such as /z/ and /v/, and the explosive release of the voiced stops /b/, /d/, and /g/. These sounds will have some periodic character because the noise generated by turbulence or explosive release is modulated by the quasiperiodic release of air due to the vibrating motion of the vocal folds.

Second, even those parts of the acoustic signal that are most periodic show highly complex wave forms. That is to say, they are not sinusoidal and, thus, analytically simple in the sense that all energy is concentrated at a single fre-

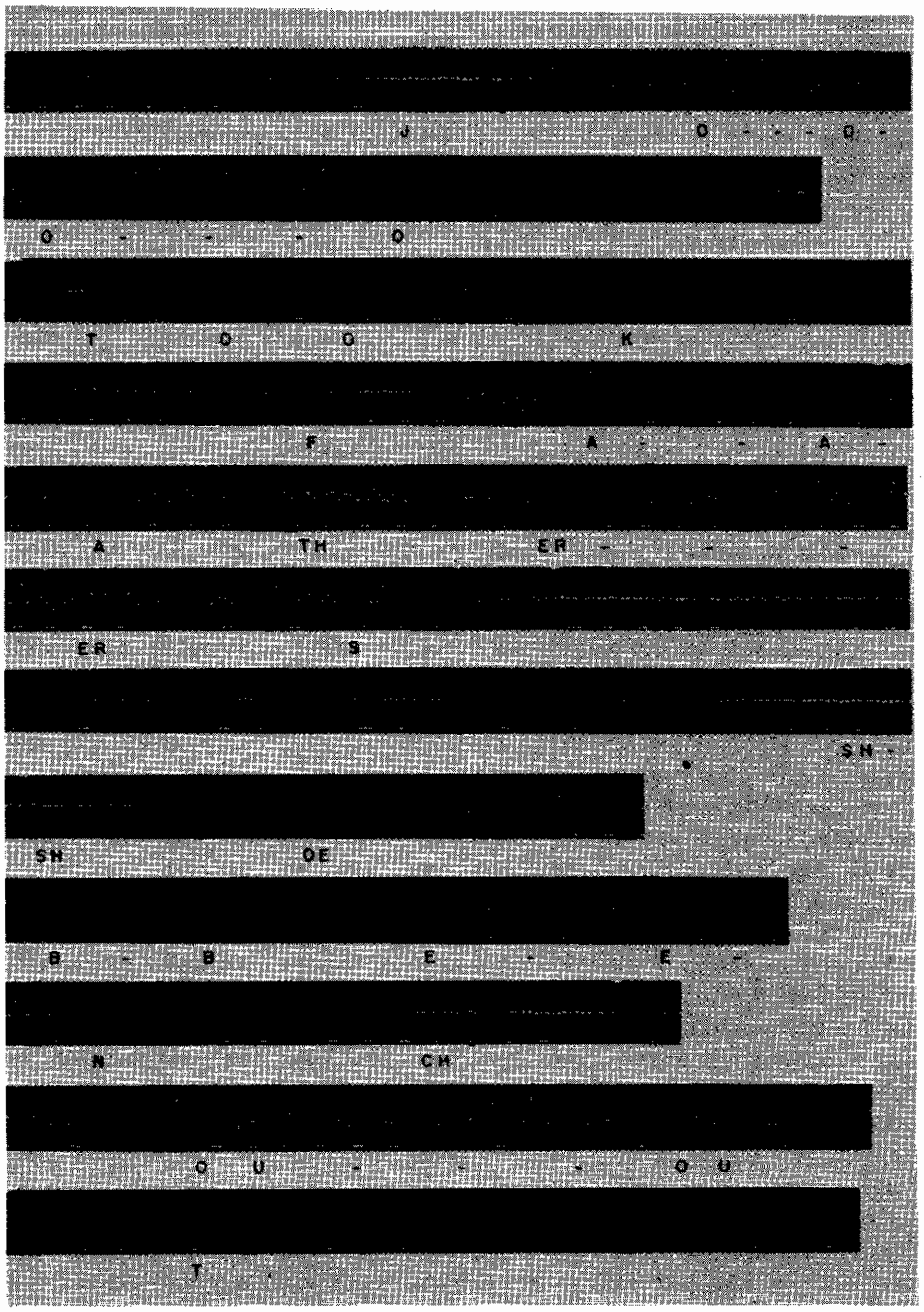

FIGURE 1. Oscillogram of a short sentence illustrating the variations of instantaneous sound pressure as a function of time during continuous speech. Dashes at bottom are time markers, each 1/120 sec.

quency. On the contrary, the complexity of these wave forms is evidence that speech signals contain energy distributed among numerous frequency components, and experiments have shown repeatedly that one of the significant ways in which speech signals are coded relates to their characteristic distributions of energy with respect to frequency, that is, the spectral characteristics of the signals.

These characteristic variations in spectral distribution may be attributed to several factors in the speech production mechanism. Certain variations are dependent on the nature of the sound generated by the source, for example, whether the source is periodic or aperiodic and other features of its vibratory characteristics. It should also be noted that for the energy from such sources to be radiated into the air it must be transmitted through some part of the vocal tract. One of the most significant facts about the vocal tract is that it constitutes a resonant transmission system—that is to say, it transmits various frequencies selectively. The particular frequencies that are transmitted most readily, depend importantly on the shaping of the vocal tract; the shaping of the tract for different speech sounds thus becomes a critical matter in relation to the spectral distribution of energy for speech.

And finally, the characteristics of the acoustic signals corresponding to speech change almost continuously in time and often at very rapid rates. On close inspection, Figure 1 shows that the acoustic signals are changing continuously in amplitude, that is, in sound intensity. This is predictable from the fact that vowels and consonants differ markedly in average intensity, over a range of as much as 40 dB. Addition of another 10 dB or so for variations in the intensity level associated with stress variation and voice level variations increases the total possible range of signal intensities to 50 dB.

Figure 1 also shows that those portions which may be characterized as relatively periodic are also changing almost continuously in another way. The repetition rate, or fundamental frequency, of the periodic wave forms of the signal, which constitutes the acoustical correlate of vocal pitch, varies almost continuously. This also can be predicted, since a speaker's vocal pitch varies constantly as he talks, both to lend expressiveness to his voice and in accordance with basic rules of inflection and intonation that are inherent in the language.

What this all adds up to is that the acoustic signals of speech, like those shown in Figure 1, are highly complex. They vary in a number of respects which are important to a full description of their characteristics as speech signals, including (1) fundamental frequency, (2) amplitude or intensity, and (3) spectral distribution. Moreover, because of their complexity and the rapidity with which they change and vary, the analysis of these signals offers some peculiarly difficult measurement problems. Special methods of acoustic analysis have had to be developed to meet the needs of researchers studying speech. For some types of analysis the techniques are still in a relatively crude and unsatisfactory state. However, developmental work on measurement techniques continues at a rapid pace. Almost inevitably, therefore, this paper will be out of date before it is in print.

Fundamental Frequency Analysis

Researchers in speech have long been interested in the analysis of the fundamental-frequency characteristics of speech, for several reasons. The frequency of vocal-fold vibration during the vocalized portions of an utterance determines the fundamental frequency of the corresponding portions of the speech wave. Hence, a measurement of fundamental frequency is important to those interested in studying laryngeal function for vocalization. For example, studies of the vocal changes that occur from infancy through childhood to adulthood are much concerned with fundamental frequency, as are studies of the effects of laryngeal changes due to disease or injuries to the larynx. Also, the perceived pitch of the voice and the variations of pitch that are involved in the patterns of stress, intonation, and vocal inflection are related directly to the fundamental-frequency characteristics of vocalized speech. Hence, fundamental frequency is one of the acoustic measurements that have basic significance in speech research.

Flanagan has stated (1965, p. 152) that the analysis of fundamental frequency of speech constitutes a very old problem, but one which is not completely solved. Solution is made more difficult because the pressure wave of speech is, as we have seen in Figure 1, a complex and only quasiperiodic function which varies with respect to time in several dimensions, including period, overall amplitude, and wave form. In a wave train showing such complexity and rapid variation, it is not only difficult to select points for measurement from successive periods, but the definition of fundamental frequency itself becomes a matter of some uncertainty. The problem is further compounded by the fact that the amplitude of the fundamental component is often quite small relative to the amplitudes of higher frequency harmonics. Attempts to improve matters by accentuating the fundamental component by wave-shaping procedures, such as filtering or equalization, have not been very successful. McKinney (1965) has provided a detailed and comprehensive review of the problems of fundamental-frequency extraction and measurement.

A large part of the available data concerning the voice fundamental has been obtained through relatively laborious techniques of manual measurement from oscillograms like that of Figure 1. Numerous attempts have been made to develop more automatic procedures for fundamental-frequency extraction (Obata and Kobayashi, 1937; Gruenz and Schott, 1949; Dempsey et al., 1950; and Dolansky, 1955). One of the more successful of these (Hollien, 1963) divides the speech signal into frequency bands by means of a set of continuous band-pass filters and samples the filter outputs by means of a switching system which automatically selects the lowest frequency filter band in which a significant output is found. The output of this filter should be the fundamental component. Its frequency then can be measured by conventional frequency-measuring networks. The band widths of the filters are chosen so that the particular filter in which the fundamental component appears should never simultaneously contain energy from any other frequency component.

This device appears to work reasonably well. Artifacts can occur, especially for high-amplitude aperiodic portions of the speech utterance. However, when artifacts occur, they tend to have values that readily can be recognized as errors and eliminated from the data.

Recently a good deal of attention has been given to developing computer techniques for fundamental-frequency analysis of speech (Gold, 1962; Noll, 1964, 1968; and Schroeder, 1968). Among the most promising of the computer-implemented techniques are the cepstrum-analysis technique described by Noll and the period-histogram and product-spectrum techniques described by Schroeder. All of these techniques transform the speech signal in a manner which utilizes the harmonic structure of vocalized sound, namely the common difference frequency among harmonics, to provide information about the fundamental period of the speech wave. The methods appear to be relatively accurate and free from artifacts. They have the virtue of providing data under adverse conditions in which the speech signal is contaminated by noise, or in which the fundamental component has very low amplitude, due either to distortion or to the inherent nature of the signal. Since the computer-implemented procedures are so new, there has been little application of them to fundamental studies of speech. It appears, however, that procedures now available permit much more rapid and less laborious analysis of fundamental frequency than was heretofore possible.

Amplitude Information—Intensity

Information concerning the amplitude variations in the speech signal is of interest to speech researchers because amplitude (or intensity) is the physical dimension that correlates most closely with the perceived loudness of speech. It also interests them because of fundamental relationships between the nature of physiological events and the variations of amplitude in the speech wave. For example, the amplitude will vary with such physiological events as change from voiced source (laryngeal vibration) to voiceless source (constricted air stream); change in subglottal pressure during laryngeal vibration; or change in transmission characteristics of the vocal tract, due, for example, to increasing constriction in the tract or coupling in a side branch such as the nasal cavities. Thus, researchers may be interested in amplitude as a dependent variable whose variations are to be studied while related variables are controlled or manipulated experimentally. They may also be interested in it as a variable to be monitored during an experiment, so that it may be kept constant or manipulated in a controlled fashion.

The complexity of speech causes real difficulty in the measurement of amplitude. To begin with, it is by no means clear that a particular amplitude characteristic of the speech wave is the most appropriate one for measurement. Are we more interested in the peak amplitude of the wave, in the average value of the complex wave, or in a root-mean-square (rms) value? Under most circumstances, the assumption usually has been made that the rms value is the most relevant, but there is little hard data on which to base such a decision.

However, even when the decision concerning peak, average, or rms has been made, the problem of implementing measurement is not simple. Almost all amplitude-measuring devices that may be used for electroacoustic analysis are wave-form sensitive; that is, the precision with which they will yield a particular type of value (peak, average, or rms) depends on the wave form being measured. They will be exact for sinusoidal wave form, but for complex wave forms their indications may depart quite markedly from true rms value, especially if the peak-to-average, or peak-to-rms, relationship is considerably different than that of a sine wave. For complex waves, such as speech, some grossness in amplitude measurements must, therefore, be accepted.

A further critical matter is the response speed and damping of the measuring device. If the device utilizes any kind of mechanical movement, its inertial characteristics inevitably influence the manner in which it follows rapid fluctuations. Since it is characteristic of speech signals that rapid fluctuations in amplitude occur as a typical matter, the indicating device must be capable of relatively fast response. On the other hand, if the response is undamped it is almost certain to overshoot whenever a sudden change in amplitude occurs, giving a spuriously large indication of change. Thus, a compromise between too little and too much damping must be made and no single compromise is optimal for all conditions.

Various types of voltmeters have been used as amplitude-indicating devices in electroacoustic circuits. Graphic level recorders which provide a permanent record of level vs time are also available. Descriptions of these devices may be found in a number of places (Steer and Hanley, 1957; Beranek, 1949). Since the indicating systems of these instruments depend on mechanical movements, the preceding discussion concerning speed of response and damping applies to all of them. A device that does not have this limitation is the Amplitude Display Unit that may be obtained as an optional accessory for the Sonagraph, manufactured by the Kay Electric Company. This device makes use of an RC integrating circuit and uses the voltage output of the integrator as a control for a level-indicating system that does not depend on mechanical movement. It provides a permanent graphical record. The level indicated is essentially a moving average of the instantaneous amplitudes summed over a time interval whose value depends on the RC time constant of the integrating circuit. The particular choice of time constant will have some influence on the values obtained, and this choice is necessarily a compromise between conflicting requirements for which no ideal solution exists.

With modern analogue-to-digital converters it should be possible to use a computer to compute almost any function of instantaneous amplitude that an experimenter might deem most appropriate for his purpose. However, I know of no one who actually has used a computer for such amplitude measurement. In most cases the requirements for precision would probably not justify the added cost.

In experiments where monitoring the amplitude of speech utterances produced by subjects is required, a very precise monitoring system is seldom needed, because the ability of subjects to control their levels is quite limited, even with considerable training. Hence, a monitoring system such as an indicating meter with appropriate averaging and damping characteristics usually will suffice.

Analysis of the Spectral Distribution

The type of acoustic analysis that is of most interest, because of its significance both in relation to the physiology of speech production and with respect to the study of speech perception, is the analysis of the frequency spectrum of the speech signal. Investigators have long realized the importance of information about the distribution of energy among the frequency components of speech. At least since the time of Helmholtz, over 100 years ago, a substantial amount of research effort has been expended investigating the spectral characteristics of speech sounds, especially vowels. Until relatively recent times such investigation was seriously handicapped by the lack of analytical techniques which could make reasonably precise measurements with rapidity and convenience. Thus, despite a considerable research effort, data accumulated slowly.

Since the development of the sound spectrograph (Koenig, Dunn, and Lacy, 1946; Kersta, 1948) and its availability in commercially manufactured models, the technological problems of spectral analysis have been reduced considerably and data concerned with the spectral characteristics of speech have accumulated at a greatly accelerated pace. During the past 20 years, the sound spectrograph has become a standard tool of the acoustic phonetics laboratory. Its general principles, its operation, and the nature of the data it yields are well known and therefore will not be described in this paper. Within its inherent limitations, it continues to be a practical research tool and doubtless will continue to find application for some time in the future. In the meantime, advances in the techniques of spectral analysis of speech have continued, and the researcher today has a choice of several procedures, especially if he has a high-speed digital computer at his disposal.

Development of Acoustic Theory

Since the 1930s there has been general agreement among students of acoustic phonetics that the major spectral features which vary systematically among vowel sounds must be related to resonances of the vocal cavity system. It was not until much later, however, that the development of an explicit theory made possible the statement of relatively exact relationships between cavity dimensions, cavity transmission characteristics, and spectral distributions of speech signals. The classic paper by Dunn (1950) represents an important landmark in the development of such a theory, since it was the first attempt to apply transmission-line theory to the mathematical description of the resonance properties of the vocal tract. The work of Fant (1960) extended this theoretical development, and also provided a substantial body of data illustrating and verifying particular aspects of the theory. Additional statements of the acoustic theory of speech based on this transmission-line model are contained in the paper by Stevens and House (1961) and Flanagan's important monograph, *Speech Analysis, Synthesis and Perception* (1965).

Analysis of System Parameters, Based on Acoustic Theory

Formant Analysis. Applied to the spectral analysis of speech signals, the currently accepted form of the acoustic theory of speech production clearly indicates that, in order to derive the most meaningful information from acoustic spectra, what is usually needed is a particular type of interpretation, which can be called *formant analysis.* The object of formant analysis is to extract from the acoustic spectrum of a speech sample the information needed for an optimally compact and precise description of the sound-transmission properties of the vocal tract. An example may help to make this clear. A non-nasal vowel constitutes the simplest case. During the utterance of a non-nasal vowel the vocal cavities may be viewed as a sound-conducting tube whose complete transmission characteristic is specified in terms of the response characteristics of its resonant modes for the vowel sound in question, also called the formants of the vocal-transmission system. In theory there will be an infinite number of such modes, but only a few of them (usually three or four) will lie within the frequency range of importance in speech analysis. The contribution of each resonant mode to the complete transmission characteristic can be represented by a response curve having a particular form, namely, the response curve of a simple, single-tuned resonator. Since its general form is fixed, the complete curve for each resonant mode can be specified by stating the values of two parameters: the resonant frequency and the band width (or damping constant). The complete curve describing the transmission characteristic for the entire system may be constructed by combining the individual curves corresponding to each of the resonant modes or formants.

Mathematically, these relationships may be most conveniently and compactly represented by equations stated in complex frequency notation. For the non-nasal vowel under consideration, the mathematical description takes the form of the product of a series of complex, conjugate poles, each of which is completely specified by two values—one corresponding to its frequency and a second corresponding to its damping constant. In the terms of this mathematical description, the purpose of formant analysis can be restated, as follows: to derive optimally precise estimates of the frequencies and band widths (or damping constants) of each of the poles that contributes significantly to the complete acoustic transmission characteristic of the vocal-cavity system. The acoustic spectra constitute raw data which may be used in deriving such estimates.

For the simple case of a non-nasal vowel that we have been considering, the vocal cavities can be idealized as a continuous tube of circular cross-section, open at one end and virtually closed at the other. It is excited at the closed end by an oscillating source (the vocal folds) which generates a complex, quasiperiodic volume velocity wave. By relatively straight forward extension, the transmission characteristics of the vocal-cavity configurations corresponding to other types of speech sounds also may be handled. For example, when a side branch, such as the nasal cavities, is coupled into the main transmission tube, the system becomes more complex and antiresonant modes as well as resonant modes contribute to the overall frequency-dependent transmission function. Antiresonant modes also are introduced when the source of energy excitation for the vocal-cavity system is located at some point other than the closed end of the tube. Such a case occurs in speech when the vocal-cavity system is excited by turbulence which results from forcing air through a narrow constriction, as in the case of a fricative consonant. In the complex frequency notation commonly employed for the mathematical description of the transmission properties of such systems, antiresonances correspond to complex, conjugate zeroes. The contribution of a zero to the complete transmission curve is exactly the reciprocal of the contribution of a pole having the same frequency and band width. It follows that, as in the case of the poles, the complete specification of the contribution of any zero (corresponding to an antiresonant mode) is determined when the value of its frequency and band width have been stated. Finally, at the risk of redundance, it may be stated that the significant parameters for determining the transmission properties of any such system having both resonant and antiresonant modes consist of the frequencies and band widths of each of the poles and the frequencies and band widths of each of the zeroes whose complex product constitutes the complete transmission characteristic.

Deriving Formant Estimates from Spectrograms. Lindblom (1962) has described in detail the problems of estimating formants from spectrographic analysis of vowels. In addition to the considerable labor required, one of the major problems is that the required parameters (pole frequencies and band widths) are not represented in a direct and simple manner in the acoustic spectrum. If the sound is a voiced sound, its acoustic spectrum will indicate energy at discrete locations (the frequencies of the harmonics) which are, of course, separated by gaps corresponding to the common difference frequency. A spectrum envelope enclosing the harmonic amplitude representations usually will show maxima which correspond more or less roughly to the resonant frequencies of the vocal-cavity system. However, because the harmonic separation in voiced sounds is relatively great (100 Hz or more) even for low-pitched male voices, there may be no harmonic that corresponds closely to the peak frequency of any particular resonant mode. The distribution of harmonic amplitudes simply does not provide a very adequate sample of the frequency-dependent variations of the vocal-cavity transmission. Because the frequency separation among harmonics is related to the fundamental frequency, this source of error is more serious as the fundamental frequency becomes higher. It is, therefore, more troublesome for the analysis of women's and children's speech than for men's. Other possible sources of error in estimating formant parameters from spectral analysis data include: (1) inadequate information concerning the spectrum of the laryngeal tone that excites the vocal-cavity system; and (2) the possibility that a zero and pole may be relatively close in frequency. If they are quite close, partial cancellation of the pole by the zero may occur. Somewhat wider separation of a pole and zero also may affect the shape of the spectrum envelope enough to cause error in estimation. As a result of these sources of error and uncertainty, estimates of formant frequency derived by simple measurement of spectral maxima are almost certain to be rough approximations. Nevertheless, a considerable amount of useful information concerning speech production has been obtained by such relatively simple procedures. For example, although the data reported by Peterson and Barney (1952) were obtained by such estimation procedures, theirs is one of the best collections of normative data for vowel formant frequencies for American speakers, and the values reported in their paper agree well with formant-frequency data estimated by more elegant procedures.

On the other hand, the estimation of formant band-width values from spectral analyses has proven to be less satisfactory and there is a great deal of disagreement among the band-width data reported by different researchers. Dunn (1961) has discussed the problems of measuring band width and has evaluated the validity of several techniques for deriving formant band-width estimates.

Analysis-by-Synthesis. A further reason for dissatisfaction with the simple procedures of estimating formant parameters from spectral data is that these methods provide no means for evaluating either the extent or direction of error in the estimates. Thus, there is no possibility of correcting the estimates to minimize the error. The development of a well-rationalized acoustic theory of speech production has presented the possibility for improving that situation, and several investigators have utilized the mathematical relations stated in the acoustic theory to develop more elegant procedures for obtaining estimates of formant parameters. Several variations of these procedures, which have been given the name *analysis-by-synthesis*, have been tried (Mathews, Miller, and David, 1961; Bell et al., 1961), but all use similar logical principles. The essentials of the method are diagrammed in Figure 2. A spectrum analysis is made of the speech sample by one of several possible methods. The spectrum derived in this analysis is used as a basis for a preliminary set of formant-parameter estimates as represented by Box 2, and is also fed to the Comparator (Box 5). The preliminary parameter estimates are entered as values in the equations used to generate a computed (synthesized) trial spectrum (Box 4), and this computed spectrum is tested by comparing it with the analyzed spectrum (Box 5). Any discrepancy between the two spectra is interpreted as indication of error in the estimated formant parameters obtained in Box 2, and an error function based on this discrepancy is calculated (Box 6). Guided by rules that adjust the formant-parameter estimates to reduce the magnitude of the error

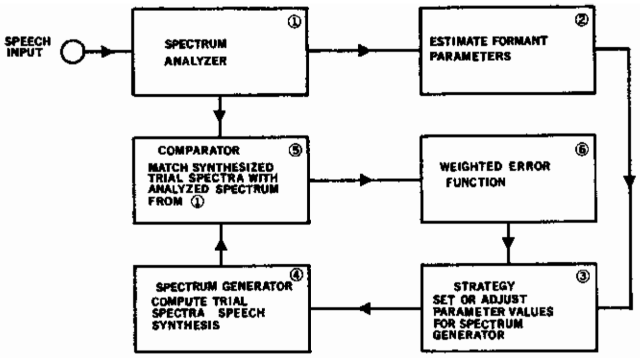

FIGURE 2. Paradigm of an analysis-by-synthesis procedure for obtaining estimates of formant parameters. (Adapted from Bell, C. G., Fujisaki, H., Heinz, J. M., Stevens, K. N., and House, A., 1961)

function, the Strategy (Box 3) determines a new set of formant parameters. The new parameters are then used to compute a second trial spectrum which is compared to the originally analyzed spectrum, and a new error function is calculated. This iterative process continues until the error function has been minimized, that is, until further adjustment in the formant parameters will no longer result in a decrease in the discrepancy between the analyzed and the synthesized spectra. These final formant-parameter values are considered the best estimates of the true values that can be obtained by the procedure.

Ideally, the error function based on any mismatch in the two spectra should indicate which formant parameters need to be corrected, and the direction and amount of correction needed. If such an ideal error function were available, only one correction cycle would be needed to achieve the optimal set of formant-parameter estimates. Since a number of parameters are involved, and their effects on the spectrum are overlapping and not easily evaluated separately, an ideal error function is not readily available. However, the iterative nature of the process compensates for the fact that the adjustments necessarily involve some trial and error. Because the process can go through as many cycles as necessary, it should usually be possible to achieve a reasonably good match.

It should be evident that the analysis-by-synthesis procedure has been made possible by the development of a mathematical theory of the acoustics of speech production. Without such a theory, the synthesis portion of the procedure (the calculation of trial spectra) could not be carried out. Also, the procedure would not be a practical one were it not for the availability of high-speed digital computers to handle the immense amount of numerical work. One of the points in the analysis-by-synthesis procedure, where variation is possible, is the stage labeled Strategy (Box 3 in Figure 2). It is here that the error function is interpreted and the formant-parameter estimates are adjusted. In some variants of the procedure, the experimenter intervenes at this point to judge the adjustments needed. It is also possible, as Paul, House, and Stevens (1964) have shown, to incorporate a set of rules into a computer program so that this stage of the process can be carried out automatically. In recent years, the techniques have had a substantial amount of application to studies in which accurate estimates of formant frequencies were required (Fujimura, 1962; Stevens and House, 1963; Stevens, House, and Paul, 1966). The experience gained so far indicates that analysis-by-synthesis procedures are quite successful in providing improved estimates of formant frequency. However, the experience also indicates that the current error-evaluating procedures are not particularly sensitive to errors in band width. Whether the sensitivity to bandwidth errors might be increased by appropriate modifications of the error function has not yet been determined.

In at least one variant of the analysis-by-synthesis procedure (Mathews, Miller, and David, 1961), an attempt was made to obtain estimates of the spectral properties of the glottal source as well as estimates of formant parameters. Up to the present time most applications of analysis-by-synthesis have been restricted to the case of non-nasal vowels. The study of nasal consonants by Fujimura (1962) is an exception. The complications introduced by the added resonances and antiresonances associated with an acoustical side branch such as the nasal cavities have thus been avoided. In principle, it should be possible to apply the procedure to nasalized speech. However, because the evaluation of error and adjustment of parameters will become increasingly complex as the number of parameters increases, the practical problems in applying analysis-by-synthesis to nasalized vowels may prove to be considerable.

The development of acoustic theory and the availability of computer technology have also prompted other attempts to improve on formant-analysis procedures. One method suggested by Pinson (1963) is of particular interest because it appears to provide a procedure for separating the spectral effects due to vocal-cavity transmission from the contribution of the glottal source, thus minimizing one source of uncertainty in estimating formant parameters—the uncertainty resulting from the fact that the glottal spectrum is not precisely known, so its effect cannot be adequately evaluated. However, Pinson's procedure can only be applied when particular assumptions concerning the glottal source characteristics are reasonable; it is not always possible to know whether these assumptions are valid for a particular sample of speech. One major advantage of the Pinson procedure may be that it appears to give more precise band-width data than can be obtained by other procedures.

Inverse Filtering. Another interesting procedure that may provide a means of separating the spectral effects due to the glottal source and the transmission characteristic of the vocal cavities has been named *inverse filtering* (Miller, 1959; Holmes, 1962; Carr and Trill, 1964). This technique processes the acoustic speech wave through a system designed to cancel the spectral contribution of the vocal-cavity transmission. The signal at the output of this network should be the volume-velocity wave generated by the glottal source. A network which will cancel the contribution of the vocal-cavity transmission should be possible if it is designed so that its response characteristics are precisely the inverse of the transmission characteristics of the vocal cavities. That is, for each pole (formant) of the vocal-cavity transmission characteristic there must be a zero in the inverse network that has identical frequency and band width. Likewise, for each zero of the transmission characteristic there must be a pole in the inverse network having the identical frequency and band width.

Figure 3 is a block diagram of a system that has been used for the inverse filtering of sustained vowels. The vowels are recorded on a magnetic tape loop and played over and over while the analysis is performed. The spectrum analyzer is used to make a preliminary analysis of formant parameters, and these are used to make initial settings of the frequencies and band widths of the four inverse filter networks. The output can be viewed on the cathode ray oscilloscope screen, and the experimenter adjusts the inverse filter frequency and band-width values until the train of pulses seen on the oscilloscope are as free as possible from residual effects that may be attributable to vocal-cavity transmission.

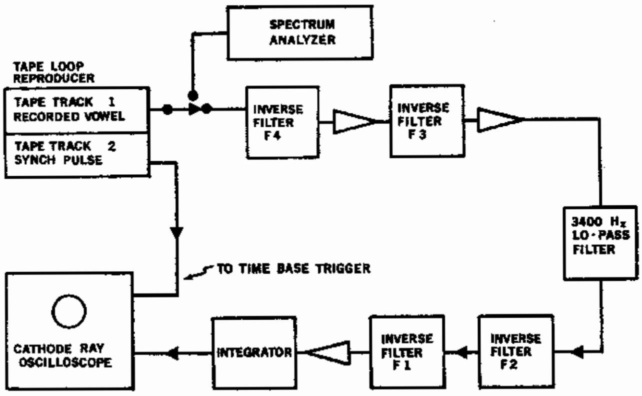

FIGURE 3. Block diagram of an inverse filter system for extracting wave forms of glottal excitation from tape recordings of sustained vowels. (Adapted from Carr, P. B., and Trill, D., 1964)

It is obvious that the output of the inverse network will be an accurate representation of the wave form generated at the glottis only if the cancellation of formant contributions is complete. This will not be possible unless the adjustments of the frequencies and band widths of the inverse networks are exact for the particular speech condition being analyzed. The ideal situation would be to have precise data concerning formant parameters in advance and to use these data for setting the parameter values of the inverse network. However, such data are generally not available. The alternative of having the experimenter observe the output and adjust the inverse network parameters until the optimum cancellation of vocal-cavity transmission has been achieved is open to certain logical criticisms. Obviously, this method requires the experimenter to make some assumptions concerning both the nature of the glottal wave that is expected and the nature of the transmission effects he is attempting to eliminate. The procedure will only be as good as these assumptions. Fortunately, our knowledge of the acoustics of speech production provides some basis for these assumptions. The general assumption is that the glottal wave form is a series of pulses, roughly triangular in form with relatively smoothly varying rise and fall phases. Oscillations (or ripples) appearing on these curves are considered to be a residual effect of resonances of the vocal-cavity transmission and, thus, characteristics that should be eliminated in the adjustment process. A second assumption is that the glottal wave form is essentially independent of the resonance characteristics of the vocal-transmission system. That is to say, there is no significant interaction between the spectrum of the acoustic wave generated by the vocal-fold vibration and the varying transmission characteristics of the vocal-cavity system. Recently, Flanagan and Landgraf (1968) have shown that this latter assumption is not completely satisfied. The inverse filtering procedure may need careful evaluation in light of their recent work.

Although the inverse filtering technique has the limitations just described, it may provide a useful alternative method for obtaining formant information as well as yielding information concerning the glottal source function. The process of adjusting the inverse filter characteristics yields estimates of formant parameters and experience indicates that the method is quite sensitive to small differences in formant-frequency adjustment. As yet there has been no adequate evaluation of the reliability and validity of any band-width estimates yielded during these adjustments.

SPEECH SYNTHESIS

Attempts to synthesize speech by means of some device that can be thought of as analogous to the human vocal mechanism were being made at least as long ago as the latter part of the 18th century, when the Hungarian, Wolfgang Von Kemplin, attempted to devise a speaking machine. Modern work on synthesized speech as a means of improving speech transmission over communication channels owes a great deal to the pioneering of Homer Dudley at the Bell Telephone Laboratories in the 1930s (Dudley, 1939). Vocal-tract analogues capable of synthesizing reasonably acceptable, human-like speech have made a substantial contribution to the development of the acoustic theory of speech production. That theory has, in turn, had an accelerating effect on work in speech synthesis. The subject is entirely too large to be treated comprehensively in a short paper; consequently, comment will be restricted to very general concepts and ideas.

Terminal Analogue Synthesizers

Analogues of the speech mechanism capable of generating reasonably humanoid speech may be classified into two general categories. Those belonging to one category, which may be labeled *terminal analogues,* are designed to provide an acoustic output that corresponds closely to intelligible, human speech by means of electrical networks that are used to generate the acoustic effects due to various components of the speech mechanism without attempting to simulate the exact processes of speech production. Such systems are likely to have the following components: (1) networks for generating a periodic source corresponding to the vocal-cord tone; (2) noise sources whose outputs represent the frictional and impulse noises generated in the oral cavity during consonant production; and (3) resonant and antiresonant networks that can simulate to a reasonably close approximation the transmission characteristics of the vocal-cavity system. In such terminal analogues, no attempt is made to simulate the dimensional and shape characteristics of the vocal-cavity system. The focus is on the acoustic output, rather than on an exact representation of the specific system from which the output is obtained in the real case. However, because terminal analogues are usually designed so major divisions of the speech production mechanism are given separate and independent representation, it is possible from experiments with such systems to derive information from which at least approximate inferences can be made about the functioning of the human system (Holmes, Mattingly, and Shearme, 1964). However, terminal analogues generally find their greatest usefulness in experiments having a primary focus on speech perception, rather than in experiments seeking to provide information about the physiology of speech production.

Geometric Analogue Synthesizers

The second type of analogue may be termed a *geometric analogue*. The significant feature of analogues of this type is that an attempt is made to represent, as completely as may be practical and acoustically significant, the geometric features of the vocal-tract system. The shape of the vocal cavities is, of course, very complex, so it is necessary to make certain simplifying assumptions in order to represent the acoustical system with electrical networks. In this simplifying and idealizing process, details should not be neglected if doing so will, in fact, distort or degrade the acoustic output of the system to a degree that would invalidate the conclusions reached from experiments in which the analogue may be used. One of the simplifying assumptions commonly made in such geometric analogues is that the vocal tract can be adequately represented as circular in cross section. For frequencies below about 5 kHz, this assumption is generally regarded as justified. The second assumption is that the vocal tract's characteristic curvature is a trivial detail, so the entire system can be reasonably represented as a straight tube. With these assumptions, the major characteristics of the vocal-cavity transmission system for non-nasal vowels can be represented as a tube of circular cross section, having varying cross-sectional area along its length. Such a model can be completely described by an area function that specifies the cross-sectional area at each point along the tube's length. This kind of geometric analogue has been implemented by a number of investigators. The early work of H. K. Dunn (1950) was particularly significant as a pioneering effort. The somewhat more elaborate geometric analogue developed by Stevens, Kasowski, and Fant (1953) has been used in a number of experiments (Stevens and House 1955, 1956; House and Stevens, 1955), and has proved useful in providing physiologic information about speech articulation. During the same period, Fant utilized a geometric analogue of the vocal tract to develop and test many of the specific relationships stated in his *Acoustic Theory of Speech Production* (1960). A natural extension of the work with geometric analogues was the addition of networks to represent the nasal cavities. Thus, experiments with the synthesis of nasalized speech could be handled, and information about the contribution of the nasal cavities to the spectral characteristics of nasalized speech was obtained (Stevens and House, 1956; House, 1957; Nakata, 1959).

Terminal vs Geometric Analogues: Relative Advantages

The geometric analogue synthesizers have the distinct advantage, as compared to terminal analogue synthesizers, of providing information which can be directly interpreted with respect to the physiological characteristics related to the shaping of the vocal tract. On the other hand, a great number of parameters must be independently controlled to vary the representation of shaping required for different speech sounds. Hence, adapting such geometric analogues to the dynamic synthesis of continuous speech presents some difficult problems. For the dynamic synthesis of speech, the terminal analogue synthesizers are more convenient and adaptable. However, by utilizing electronically variable reactance networks, Rosen (1958) designed a dynamic geometric analogue that was programmed to produce two-element (consonant-vowel or vowel-consonant) syllables. Hecker (1962) added a nasal-cavity analogue with a dynamically variable representation of the nasopharyngeal valve, and used it to produce two-element synthesized syllables with nasal consonants. To reduce the number of parameters, some detail in the analogue representation of the actual vocal-tract geometry was sacrificed. Even with this simplification, 11 variable parameters had to be manipulated simultaneously—a large number for convenient programming. Recently, experimenters at the Bell Telephone Laboratories (Coker, 1967, 1969) have initiated new experiments that can reasonably be classed as geometric analogue experiments. Because these experiments are implemented by means of a high-speed digital computer, they will be discussed in the next section, which is concerned with the application of digital computers to acoustic and analogue studies in speech.

Synthesis of Articulatory Shapes from Acoustic Data

One of the most significant contributions of the modern mathematical theory of speech production is the exact statement of the relationship between the shaping of the vocal tract (as represented by the vocal-tract area function) and the transmission characteristic of the tract. The theory makes it clear that corresponding to any particular vocal-tract area function there is a unique solution of the vocal tract's transmission characteristic. That is, given a particular articulatory shaping, and a specified input to the vocal tract, the acoustic characteristics of the output are completely determined and can be calculated exactly.

On the other hand, it usually has been accepted that the converse is not possible. That is to say, a specified acoustic output can be produced as a product of several different vocal-tract shapes. Stated somewhat differently, there is no single unique articulatory configuration that corresponds to a particular vocal tract's transmission characteristic.

Recent work (Mermelstein and Schroeder, 1965; Mermelstein, 1967; Schroeder, 1967; Paige and Zue, 1969; Atal, 1969a,b) now opens up the possibility that by introducing certain constraints that are entirely appropriate for the particular case of speech articulation, the ambiguous possible cases may be excluded and the calculation of articulatory shapes from acoustic data may yield a unique solution.

Although this work is still in an early stage, it has been carried far enough to indicate that, in the relatively near future, one may be able to derive information about dynamic articulatory events from acoustic analysis. Th advantages of such procedures are obvious: they do not require the use of apparatus that may interfere with or distort articulatory events (face masks, sensing devices inserted into a subject's mouth, etc.). Nor do they involve risks such as exposure to x ray. Moreover, it seems quite possible that, in some respects at least, the data obtained may be more complete than data obtained by cineradiography, since they will not involve the limitations of a two-dimensional representation. Thus, we have the promise of a new technique that should make possible the use of acoustic analysis to achieve new and better information concerning the physiological events of speech production.

DIGITAL COMPUTER APPLICATIONS

The impact of the high-speed digital computer on acoustic research in speech has been very great, as it has in almost every other field of research. Not entirely fortuitously, the development of computer technology and the development of a well-rationalized theory of the acoustics of speech production coincided in a number of ways. Much recent research has been the result of their joint impact. Some of the ways in which acoustical studies of speech have benefited from high-speed digital computers have been mentioned already—for example, the use of digital computers in implementing fundamental-frequency extraction techniques and in formant-estimation procedures utilizing analysis-by-synthesis. Although, in theory, these analytic procedures would be possible without digital computers, the calculations required would be so time-consuming that they would be completely impractical.

Computer implementation of the acoustical analysis of speech has also been aided greatly by the development of efficient, practical, and reasonably inexpensive analogue-to-digital and digital-to-analogue conversion devices. By means of such input-output devices, the computer can accept the signal generated from a microphone, convert this analogue signal to digital form, and perform whatever operations or calculations may be required. If desired, the result of such operations can then be reconverted to an analogue voltage and reproduced as sound.

Another significant development in computer technology is computer simulation of complex systems. Until recently, speech synthesis employing either the terminal analogue or geometric analogue type of synthesizing process required that the actual electrical synthesizing circuits be built. It is now possible to represent the functioning of such networks by means of appropriate equations. The computer can be programmed to handle the corresponding numerical operations with great ease and speed and, thus, the actual electrical circuit representation may not need to be built.

A particular application of computer simulation is the technique that may be termed *computer modeling*. In recent years, computer modeling has been applied to research in speech production by several investigators who have begun some unusually interesting and promising experiments. Computer modeling has the special virtue of making it relatively easy to vary the mathematical or graphical representation of a conceptual model of a system and to assess very quickly the effects of such variations. One example is the work of Henke (1967). He has experimented with a procedure for representing the midsagittal section of the vocal tract as a two-dimensional graphical display through the use of an oscilloscope and light pen as an input-output device to a computer. His conceptual model includes a set of parameters that may be varied dynamically to alter the shaping of the vocal tract simulating its function in speech articulation. It also includes a set of rules for altering the control parameters. Henke's published results indicate that his methods have been applied only to very simple speech utterances. However, the approach is extremely interesting and seems to have considerable promise for increasing our understanding of the dynamics of speech production. Apparently, Henke has not attempted to derive an acoustic output for his dynamic articulatory model, but this would appear to be a possible extention for future experiments.

Coker and his associates at the Bell Telephone Laboratories (Coker, 1967, 1969) have developed a somewhat different version of a dynamically controllable, computer-simulated model of the vocal tract. Their reports indicate that they have devised programs for varying the vocal-tract simulation dynamically by means of parameters that correspond to articulatory variables. They then compute the variations in vocal-tract geometry which result from the articulatory variations, derive the dynamic vocal-tract area function, and utilize the area function to calculate the acoustic output. The calculated acoustic output is then converted to an analogue voltage and reproduced as audible speech. By this procedure they have succeeded in synthesizing continuous speech, using a geometric analogue that not only can be varied and controlled dynamically, but functions in relation to parameters that may represent realistic articulatory variables. It should be noted that the speech synthesized by this system is quite convincing. That is, it sounds relatively intelligible and humanlike. As yet, an analogue of the nasal cavities has not been included in the model, but the principles being used should be capable of extension to permit experimentation with nasalized speech.

Other contributions of computer technology that have been important in acoustic studies of speech include the following: (1) The development of special analyzing procedures such as the Fast Fourier Transform (Cooley and Tukey, 1965). Such procedures open up new possibilities for acoustic analysis, especially more rapid and efficient methods of spectrum analysis. (2) The development of procedures for controlling external apparatus by means of computer-generated signals. A special application is computer control of speech synthesizers (Mattingly, 1967; Haggard and Mattingly, 1968). This significant advance enables an experimenter to control more parameters simultaneously, with greater ease and flexibility than is possible by other means. Thus, with computer control, it should be possible to approximate more closely the dynamic variations produced by the actual human vocal apparatus, making analogue experiments more nearly representative of real speech. Much of the work in dynamic speech synthesis, or synthesis by rule as it is commonly known, now makes use of such control by a programmed computer.

A LOOK AHEAD

It should be evident from the foregoing remarks that the advances in research technology made during recent years open up many new and exciting possibilities in research on the acoustics of speech production. The researcher has tools at his disposal that should make possible a significant increase in the precision and speed with which relevant observations may be made. During the period through which we have been passing, developments in research techniques have been so rapid that there has not been time for researchers to utilize these new tools fully, so the potential contributions of these technological developments have only begun to be felt.

During the same recent past, as we have seen, there have also been noteworthy strides in the development of comprehensive theory relating the physiological events of speech production to the acoustical signal produced by the physiological system. Thus, researchers have a basis for formulating experiments with greater assurance that their assumptions are reasonable, that their hypotheses and predictions have a reasonable chance to be verified, and that their observations and measurements, and the resulting descriptions of processes and relationships, will ultimately prove to be scientifically relevant.

With this state of affairs, it seems more than a little presumptuous to forecast the directions that research in this area will, or should, take in the immediate future. A few general statements can be made, simply on the basis of the research tools now available. I shall attempt no more by way of prognostication than the statement of a few such general and probably obvious points.

First, research in speech synthesis has achieved a stage of development through computer simulation and computer-programmed control which now makes possible increasingly complex and sophisticated experiments. Moreover, in computer-simulated synthesis it has become possible to represent physiological parameters with increasing faithfulness and precision. As a consequence, it seems highly probable that future experiments concerning the relationships between physiological processes and the acoustic signal will increasingly make use of speech synthesis as the experimental procedure of choice.

Almost a corollary of this first point is a second general statement concerning the studies and information to be developed in the future. It is to be expected that there will be increasing emphasis on the dynamics of the processes. In the past, because of the inherent limitations of the available research tools, observations often had to be limited to the state of affairs at discrete points in time. In general these limitations are no longer effective. Through dynamic speech synthesis experiments we can control the physiological speech production parameters (or their analogue representations) dynamically; we can observe the changes in the time series that constitutes the acoustic signal; and we can test the validity of these observations against real speech in several ways. By such means we should be able to achieve new understanding of the timing of the physiological events involved in speech production and to obtain better answers to such questions as the following: How rapidly do articulatory events take place? In what order? How much overlapping and interaction is characteristic of dynamic speech processes? What are the appropriate units for time analysis? Can speech be analyzed as a series of discrete units, or does it consist of elements that are shingled together in a complex time series of overlapping and interacting events?

Such questions have both theoretical and practical significance. Answers to them will help us refine our theoretical models of speech production processes. They should also help us understand and describe the anatomical and physiological requirements for a mechanism that is capable of producing acceptable speech.

Third, it should be evident that in the future acoustic and analogue studies, particularly speech synthesis experiments, will become increasingly important as a means of studying physiological variables. As anyone who has been involved in speech research knows full well, one of the major problems in studying speech production processes is the inaccessibility of the system to direct observation. Techniques, such as cineradiography, are only a partial answer to this problem. They have their own well-known limitations. Because of the partial nature of the data yielded by such procedures, the interpretations and conceptualizations of speech production events derived from them need to be verified by independent means. The recent development of acoustic analysis procedures and analogue synthesis studies indicates that these procedures provide one means, at least, of independent verification. In recent years there has been an increasing tendency for researchers to use cineradiographic and acoustic analysis techniques as mutually supplementing observational techniques to obtain related data concerning articulatory process (Heinz and Stevens, 1965; Ohman, 1966, 1967). This tendency will doubtless increase in the future. In addition, as we have seen, new techniques are being developed that may make possible the utilization of acoustic data to provide information about articulatory events which are otherwise very difficult if not impossible, to observe. Thus, in the future, we may expect to see the analysis of the acoustic output of speech playing a new, and possibly even more significant, role in our search for a comprehensive description of speech production processes.

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ASSESSMENT: RADIOGRAPHIC TECHNIQUES

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Few events in the history of science have had so powerful an impact as the discovery of the x ray by Wilhelm Conrad Roentgen, Professor of Physics at Wurzburg, Germany, on November 8, 1895. This discovery marked the end of the classical era of physics (including belief in the existence of luminiferous ether) and the beginning of x-ray spectra studies which unlocked the secrets of atomic structure. It also had almost immediate research application to the scientific study of normal and abnormal speech and other functions of the dentofacial complex. Radiographic assessment techniques have provided a major method for research workers interested in speech and other functions of the structures of the stomatognathic system of common interest to speech pathology and dentistry alike for over 75 years.

This paper presents a selective review of the nature, limitations, early history, and current state of the art of radiographic research in this area. It includes a critical, selected review of the major findings and controversies reported in the literature, leading to some recommendations for future investigations.

NATURE, LIMITATIONS, AND EARLY HISTORY

Roentgen called his newly discovered rays x rays because their nature was unknown in 1895. If one attempts to understand the true nature of x rays today, he will still end up in the unknown after traveling through the seven regions of the spectrum of electromagnetic radiation theory (in order of decreasing wavelength) from (1) radio waves, (2) radiant heat, (3) infrared radiation, (4) visible light, (5) ultraviolet light, and (6) the far-ultraviolet or Millikan region, to (7) x rays and gamma rays. The search ends in the Bohr-Heisenberg Uncertainty Principle, which states that both radiation and matter act like particles; but, at one and the same time, both have the characteristics of waves.

X rays are therefore a form of electromagnetic radiation. They are produced in radiographic instruments by directing a stream of electrons against a target in a vacuum tube. Electrons within the atoms of the target are caused to emit certain defined wavelengths in the x-ray spectrum by such bombardment. The emitted rays are of the order of 250,000,000 or more waves to the inch, as compared with 50,000 waves to the inch for visible light. They penetrate all body structures to varying degrees. An image of the structures within the human body either can be made visible on films with emulsions such as silver halide or can be visualized on a fluoroscopic screen after x rays pass through the body. In the simplest of terms, x-ray assessment techniques provide a "window" for the study of the function of the organs of speech of living subjects which cannot otherwise be seen or studied without interfering with normal function.

Limitations

The assessment of functions of the structures of the dentofacial complex through radiological methods has certain inherent limitations. A list of these limitations useful for a critical evaluation of the literature should include the following considerations:

1. The image on film or fluoroscope is always a two-dimensional picture of the three-dimensional dentofacial structures and therefore is an incomplete representation.
2. Correction factors must be determined for each radiographic system for studies involving biometric analysis of images of structures. The straight line emission characteristics of x rays originating from a point across the body cause relative enlargement of the periphery.
3. Danger from radiation exposure requires thoughtful and strict limitations on research subjects and length of speech sample studied. Careful calibration, radiation monitoring, filtering and protection, and supervision of data collection should be conducted by qualified radiologists. For a current review of the issues involved, the reader is referred to Holcomb (1970).
4. The time requirements of the majority of regular radiographic techniques (including cephalometric procedures which produce the clearest standardized measures of the oral-facial complex) are such that only nondynamic speech functions on sustained sounds can usually be validly studied.
5. Laminagraphy techniques including planigraphy, tomography, stratigraphy, and verigraphy which offer potential applications for examining dental-oral-facial structures in planes (lamina) which cannot be visualized by regular radiographic procedures or in cinefluorography require too much time for the rotation of the x-ray source or photographic plate during filming to investigate most dynamic aspects of speech production.
6. The modern cinefluoroscopic techniques which do allow for visualization of motion patterns of organs during more natural acts of connected speech do not produce as clear reproductions as standard radiographic techniques because of inherent ionization characteristics of fluorescence and due to other technical problems. Telefluoroscopic units which further reduce radia-

tion hazard have the added disadvantage of not allowing for frame-by-frame biometric analysis.

7. The requirements for stabilization of the body for reliable studies limit observations of the functions of the oral structures to one body position for each study. The same functions may differ (due to changes in antigravity muscle functions, and so on) in different body positions.
8. Variations in radiopacity from individual to individual result in the varying degrees of clearness of radiographs of all types affecting the reliability of data abstracted on groups of subjects.
9. A large amount of detailed hand tracing and measuring by trained research investigators is still required in studies of limited population samples of controlled speech even with the most current cinefluorographic analysis systems as used by Perkell (1969).

Further limitations of radiographic assessment methods result from the complex nature of energy systems involved in acts of human communication through speech. In the process of speaking, energy in the form of patterns of chemical-electrical discharges in the central nervous system which might be studied through electroencephalographic recordings are transformed into patterned multiple neuromuscular energy which can be measured at specific muscles by electromyographic recordings. Muscular contractions throughout the organs of respiration, phonation, and articulation only then result in movement patterns of the organs of speech which can be studied in part through radiographic assessment techniques. Relations of organ movement patterns to airflow and acoustic energy within and outside of the human body requires correlated data from other assessment techniques synchronized with the x-ray data. The acoustic energy perceived by a listener can be categorized into linguistic units and rated on quality judgment scales. Clearly, only combined systems comparing data from x-ray assessment techniques with data from measures of one or more of these several related energy forms involved in speech can be used to study even a small part of the complex behavior we call speech.

Early Radiographic Research

The pioneer investigator in speech science research through radiographic techniques was Max Scheier, who published his first paper on the topic "The application of X-ray in the physiology of the voice and speech" in Berlin, Germany, only a year and a half after the discovery of x rays (Scheier, 1897). Scheier's considerable contributions over the following 10-year period initiated or predicted the full scope of possibilities of radiographic research in this area. He also considered some of the major technical problems needing further solution even today. A review in some detail of his work and that of his major contemporaries using radiographic techniques can be found in MacMillian and Kelemen (1952).

The earliest interest of research investigators was to study the role of the tongue in speech. Phonetic scientists attempted to define the role of tongue placement for individual speech sounds, especially for the vowels. By measuring vertical distance on radiographs between the high point of the tongue and a stable reference line, such investigators as Russell (1928, 1929), Parmenter and Trevino (1932), and Carmody and Holbrook (1937) presented contradictory conclusions based on extensive x-ray data. However, by the time of the report of Chiba and Kahiyama (1941) it had become established that a characteristic posture is maintained by the tongue for the production of different vowels if the position of the head and body are standardized and controlled for the collection of x-ray records. Russell (1928) had collected and studied over 3000 research x-ray films on more than 400 subjects and yet falsely concluded—because of his lack of standardization and stabilization of his subjects' head and body positions—that definite relationships between tongue positions and vowels did not exist. A more detailed critical review of the early contributions of Russell, Parmenter and Trevino, Carmody, and their contemporary workers can be found in Subtelny (1961).

RECENT AND CURRENT RESEARCH: TECHNOLOGICAL ADVANCEMENTS, MAJOR FINDINGS, AND ISSUES

Radiographic Instruments

Three basic types of radiographic instruments are available to the research investigator today. These can be listed as routine or "still" x-ray techniques including standardized cephalometric units, the more recent "motion-study" instruments for cineradiographic or cinefluoroscopic records, and the "sectioning" instruments of laminagraphy and related techniques.

Still X Rays and Cephalometrics. The still x-ray techniques were naturally the first to be used in speech science research. The basic standardized techniques of cephalometrics of special importance to the topic of this workshop can be found in papers by Broadbent (1931) and Brodie (1949). Cephalometric techniques were popular with researchers before the advent of cinefluorography, are more generally available, and still have the advantages of better resolution of the image. Graber (1952) lists, defines, and illustrates the anthropometric and cephalometric measure points that have been developed to standardize information on the dentofacial structures from lateral still x rays. Wildman (1961) proposed a standardization of measurements like those used in cephalometrics for lateral laminagraphy and for cinefluorography. Sloan et al. (1964) also described an application of cephalometric techniques for cinefluorographic speech studies. Lubker and Morris (1968) have reported a study of the best methods of predicting cinefluorographic measures of velopharyngeal function from lateral still x-ray films.

Cinefluorography. Cinefluorography has the great advantage of adding the dimension of motion study of the organs of speech through x-ray pictures. Cineradiography techniques were first used but these presented too great a radiation hazard for the length of studies needed. Carrell (1952) described a technique for reducing radiation effects by synchronizing the roentgen generator and the picture and commended the general advantages of cineradiography for the evaluation of velopharyngeal closure inadequacies.

It was the development of electronic image intensification that made cinefluorography a practicable technique for speech science research. The weak image formed on the fluoroscopic screen by the passage of fewer x rays through the subject than required for radiography now can be intensified 1000 or more times in brightness by means of an electron optical intensifier. Berry and Hofmann (1956, 1959) have described the principle of image intensification and other details of the cinefluorographic techniques for research on the function of the organs of speech. Details of procedures of cinefluorographic research are also presented by Ohman and Stevens (1963).

Methodological studies to determine the necessary and the most effective filming rate for studying speech functions were reported in papers by Moll (1960), Bjork (1961), Bjork and Nylen (1963), and Shelton, Brooks, and Youngstrom (1964). The desirability of rates of 60 fps (frames per second) and faster for the study of rapid articulatory movements is generally advocated. However, Sparrow, Brogdon, and Bzoch (1964) found that for specific studies of normal velopharyngeal function a filming rate of 30 fps produced the same data as a filming rate of 60 fps. The rate of 30 fps allowed for recording of a synchronized sound tract for correlative analysis and may therefore be preferred for certain investigations.

Moll (1960) reported procedural techniques for obtaining clear cinefluorographic pictures and for extracting reliable information by specific measurements taken from tracings of film projections. Other papers useful for technical information on equipment and methods of procedures to be used in quantitative cinefluorographic studies include Powers (1960), Bjork (1961), Warren and Hofmann (1961), Jakobson, Fant, and Halle (1961), Sparrow, Brogdon, and Bzoch (1964), and McWilliams, Musgrave, and Crozier (1968). The last paper describes the effects of changes in head position upon velopharyngeal function with a teleradiographic instrumental procedure. McWilliams and Bradley (1964) developed and reported a reliable rating-scale method of data reduction from teleradiographic records since these do not allow for frame-by-frame quantitative analysis. Williams (1969) recently has reported reliability of another rating scale of tongue carriage and movement patterns which simplifies cinefluorographic data analysis for certain comparative studies.

Laminagraphy. Subtelny, Pruzansky, and Subtelny (1957) and Moll (1965) are sources for general descriptions of laminagraphy techniques available for sectioning studies. Examples of laminagraphic studies of speech functions can be found in Hollien and Curtis (1960) and Hollien and Colton (1969). The technical distinctions between the techniques of planigraphy, tomography, stratigraphy, and verigraphy are illustrated in the book *Dental Roentgenology,* by Ennis, Berry, and Phillip (1967). A description of the instrumentation and an application of stroboscopic laminagraphy (STROL) is presented in a paper by Hollien, Curtis, and Coleman (1968).

Significant Studies Using Radiographic Instruments

In the current state of the art, refined radiographic assessment techniques are being used to define coarticulation patterns of the organs of speech, to generate theories of underlying mechanisms testable with correlated studies combining newer assessment techniques like electromyography or sound spectrography, and to further define parameters of normal and abnormal speech physiology.

A critical review of the pertinent literature indicates that radiographic investigations have made many important contributions to our present understanding of both normal and abnormal physiologic functions involved in speech production. However, the majority of the past publications are characterized by over-enthusiastic descriptions of radiographic equipment or special methods of x-ray research to be used to unlock the secrets of the communication process in human beings or by over-generalizations regarding normal or abnormal speech physiology from very limited radiographic data. Much more basic descriptive, correlative, and experimental research with radiographic methods of investigation remains to be done. The newer refined "windows" to the inside functions of the dentofacial structures, and the recent development of more automatic systems of data reduction, storage, and retrieval hold great promise for such future research applications. The following review of radiographic investigations emphasizes lingual and palatal function studies including "tongue thrust" and "cleft palate" at the expense of some important related areas like laryngeal or breathing-function studies, in order to keep within the required limits and emphasis of this workshop.

Studies of Normal and Abnormal Lingual Functions. While the early studies up to 1940 concentrated on tongue positions for given sounds, the more recent and current investigations are now focused on more complex analysis of coarticulating lingual functions on a time base with correlation studies from synchronized sound tract recordings. Attention also has been directed toward studying abnormal lingual functions in "tongue thrust," cleft palate, and other clinical disorder categories. Lindblom (1964), for example, studied the effects of different sound environments on the characteristic tongue positions for vowels. Refined studies of normal physiologic phonetic descriptions of basic target positions, and modifications of these from the coarticulation effects of adjacent consonants, began to be reported in the early 1960s. The report of Houde (1968) is one good example of modern combined radiography and spectrographic systems and the use of radiographic markers to study lingual functions. A frame-by-frame analysis of approximately 7000 frames of film was made to study horizontal and vertical displacements by use of a coordinate system. 100,000 individual coordinate measurements were collected, recorded on punch cards, and plotted by a digital computer for the analysis. With this more sophisticated technique it was possible to identify target positions for each of the five tongue markers during the production of each phoneme and to develop a model of tongue body articulation from the data.

Stevens (1963) helped initiate radiographic coarticulation studies through a frame-by-frame analysis of cinefluorographic films for four utterances by one speaker, reporting variations of both tongue tip and pharyngeal activity. He found that the sound environment influenced the rate of tongue-tip motion for the production of /t/.

Coarticulation variations in normal speech for both vowels and consonants are still a subject of special interest to acoustic and physiological phonetics. Finer variations can now be studied, since working definitions of basic tongue target positions for their productions now exist.

Tongue-Thrust Studies. A considerable literature about tongue functions of importance to dentistry and speech pathology alike is concerned with what is usually called "tongue thrusting." Tongue thrusting is usually defined as an abnormal swallowing pattern in which lingual pressure is exerted upon the anterior teeth (Palmer, 1962). For the most part is has been regarded as a habit in normal children rather than a pattern determined by physical or physiological disorders, although Bloomer (1963) suggested that there may be a neurogenic basis for the establishment of this pattern.

No objective investigations of the assertions, assumptions, and generalizations regarding what is called tongue thrusting and the speech and dental structure effects of this behavior have been reported to date, in my judgment. Clearly, x-ray methods of investigations could help resolve many of the related issues reviewed elsewhere in this *Report.*

Abnormal Lingual Patterns in Cleft-Palate Subjects. Cleft-palate speech is characterized by both abnormal voice quality and defective articulation. Unusual types of misarticulations frequently encountered in preschool cleft-palate children have been reported by Bzoch (1956), Spriestersbach, Darley, and Rouse (1956), and Olson (1965). It might be assumed that such abnormal articulation patterns result from or cause either organic or physiologic differences in the tongue or that they are learned in compensatory attempts to produce clear speech before velopharyngeal incompetency is corrected. Positive relationships between adequacy of velopharyngeal function and the degree of aberrant articulation for cleft-palate speakers have been reported by Counihan (1956), Hagerty and Hoffmeister (1954), and Spriestersbach and Powers (1959). These authors established the degree of velopharyngeal insufficiency from measurements of x rays.

Possible relationships between abnormal tongue carriage and the perception of hypernasal distortion of voice quality in cleft-palate speakers need further study and verification. Hixon (1949), in a study of hypernasal speakers without cleft palate, reported a high carriage of the rear of the tongue and theorized that this abnormal tongue position altered the oral-nasal resonance balance, causing an increase in perceived hypernasality. Williamson (1944) and Van Riper (1947) have suggested possible similar relationships between these factors. McDonald and Baker (1951) similarly hypothesized that nasality in cleft-palate speech is related to the abnormal position and movement of the mandible and tongue. Koepp-Baker (1957) suggested that the modified tongue and mandibular positions may actually "affect the position from which lingual movement sequences start and to which they return." Buck (1953) investigated tongue carriage abnormalities of cleft-palate speakers through data from cephalometric x rays. He found that the cleft-palate group in his study actually had significantly lower tongue positions during rest, and for sustained vowel productions of /ae/ and /u/ than normal controls. This was in disagreement with the previous observation reports. He also found that the cleft-palate subjects carried the tongue significantly farther forward for the vowels /a/, /i/, and /u/ than did the normals.

Powers (1960) conducted a cinefluorographic study on articulatory movements of cleft-palate speakers and analyzed differences within this group. He concluded that his subjects were homogenous in reference to lingual articulatory movements. Analysis of short utterances of connected speech indicated a high-back tongue carriage was common.

Brooks, Shelton, and Youngstrom (1965), using the technique of cinefluorography, made frame-by-frame measurements of the anteroposterior tongue movement as demonstrated by changes in the tongue-pharyngeal wall gap. The totals of these measurements were averaged as an index for mean tongue movement for the clinical and control normal groups. No differences were found for cleft-palate subjects; however, the use of mean scores as a method of analysis might have obscured some differences.

Peat (1968), in a cephalometric study of tongue position, observed two postural positions of the tongue existing for all individuals. These were termed *habitual,* in which the tip of the tongue makes contact with the incisors, and *relaxed,* in which (1) a high percentage of the subjects do not make lingual-incisor contact, and (2) a separation develops between the dorsum of the tongue and the hard palate.

Perkell (1969) reported findings of a detailed analysis of the lingual movements of one normal speaker through 13 speech utterances. The data in his report were used mainly to develop a theory of central mechanisms involved in speech production.

Williams (1969) reported a cinefluoroscopic investigation of lingual speech functions of groups of both cleft-palate and normal subjects. He used and compared two methods of data analysis of standardized and controlled cinefluorographic films. Twenty-six subjects, including 10 control and 16 postoperative cleft-palate patients, were studied. Six judges were asked to classify the perceived direction of lingual movement during the speech sample as either "front-to-back" or "back-to-front" and also were required to classify tongue carriage as predominantly "front," "middle," or "back." Midsagittal tracings were made of five frames representing the optimal articulatory contacts for the sounds /k/, /w/, /z/, /t/, and /v/ from a standard speech utterance. Objective measurements were also defined and made from the cinefluorographic tracings on tongue carriage of each subject. Findings from this cinefluoroscopic study reported by Williams (1969) include:

1. There were distinctively different features of lingual articulation occurring for the selected control subjects and for the postoperative cleft-palate speakers.
2. The agreement between judgments and objective measures was high enough to conclude that judges can be reliably employed in classification tasks involving lingual movement and carriage differences in x-ray motion studies of population samples.
3. The pattern of lingual movement in connected speech for the control subjects was described as an overall front-to-back motion, while the overall pattern of lingual movement in connected speech of the postoperative cleft-palate speakers was described as back-to-front.
4. There was only one recognizable pattern of lingual carriage in connected speech for the control speakers which could be described as "midcarriage" but there were two different patterns of lingual carriage in connected speech for the postoperative cleft-palate speakers; one described as "front" and the other as "back" carriage.

Malocclusion, Missing Teeth, and Speech. Another important area for current and future radiographic investigations is the study of the interrelationships between malocclusion, missing teeth, dental prostheses, and speech. Fymbo (1936) questioned the relationship between defective speech and malocclusion. Later investigators including Froeschels and Jellinek (1941), Gardner (1949), Fairbanks and Lintner (1951), Powers (1957), and Bloomer (1957) generally concluded that there appear to be some positive relationships between the severity of articulation disorders of speech and dental defects. Whether there exist any cause-and-effect relationships remains a controversial question today. Bankson and Byrne (1962) have reported positive cause-effect interrelationships between defective articulation of /s/ and the loss of the incisors. Froeschels and Jellinek (1941) earlier stated that interdental lisping for such silibant sounds as /s/ and /z/ could actually cause dental malocclusion. Powers (1957), however, has claimed that malocclusions cannot be considered a cause of misarticulations since many speakers with gross malocclusions are able to make compensatory adjustments and produce normal speech.

Benedicktsson (1958) has suggested that speakers with severe maxillary overjet must protrude the mandible to articulate the /s/ sound clearly in speech. However, the x-ray study of Subtelny, Mestre, and Subtelny (1964) does not support this. Of 31 normal speakers with maxillary overjet, they found only one demonstrated abnormal protrusion of the jaw during /s/ sound production. More objective studies are needed and x-ray methods of assessment offer a means of objective investigation.

STUDIES OF NORMAL AND ABNORMAL VELOPHARYNGEAL FUNCTIONS

Radiographic techniques have been a major method of assessment for studies of the functions of the soft palate and related structures in speech. Studies of both normal and abnormal velopharyngeal function are of major importance to the clinical sciences of dentistry and speech pathology. The areas for investigation of the velopharyngeal mechanism for speech have been extremely broad in scope. There are still many unanswered questions regarding the parameters of normal and abnormal velopharyngeal functions for speech.

The following review of the pertinent literature is organized in terms of four major broad research questions to highlight the issues within each remaining to be solved. The big questions are these:

1. Is complete velopharyngeal closure necessary for clear speech?
2. What are the major parameters of velopharyngeal valving in normal speech patterns, and what are the major factors which affect these parameters?
3. What are the major phonetic and coarticulation effects on velopharyngeal valving for speech? and
4. What is velopharyngeal insufficiency for speech and what are its effects on articulation and its acoustic and perceptual correlates?

Is Complete Velopharyngeal Closure Necessary?

The basic question of whether complete closure of the velopharyngeal port is necessary for the production of speech perceived as normal has not been answered fully as yet. Earlier x-ray research pertaining to this question was based on still radiographic techniques of sustained vowels. Inconsistent closure of the velopharyngeal mechanism was found during sustained vowel sounds in many speakers with normal voice quality. This finding has been interpreted to indicate that complete seal of the nasopharynx was not necessary or even typical of normal speech behavior. However, Bzoch (1960) reported that complete closure was always found for 50 normal subjects when high-speed cephalometric x-ray films were exposed while the subjects were repeating CV syllables with the consonants /p/, /b/, /f/, or /w/ and the vowel /i/. He reported that velopharyngeal closure was not consistently found for the same subjects on the sustained vowel /i/. Moll (1962) reported similar findings with cinefluoroscopic techniques. Closure during the phonation of sustained sounds is not necessarily identical with that found for the same sounds by the same speakers in connected speech.

Bjork (1961) reported finding openings in the velopharyngeal port only for nasal consonants and neighboring vowels in his cinefluoroscopic analysis of the production of four sentences by normal Swedish speakers. However, Bjork and Nylen (1963) reported that some persons with normal speech produced some of the consonants /k/, /v/, /s/, /t/, /b/, and /d/ which were perceived as correct, without complete velopharyngeal closure, as seen with cinefluorography. It is not clear whether these sounds were adjacent to nasal consonants or were ending speech utterances—two conditions which Bzoch (1967) reported could result in "pressure" consonants being produced during a period when the velopharyngeal seal was open. Bzoch (1968) has subsequently reported cinefluorographic studies of 100 normal-speaking adults which revealed all subjects obtained complete velopharyngeal closure for speech during the same critical portions of a standard speech phrase. All subjects had an identical movement or coarticulation pattern involving three periods of complete closure and four periods of opening, as shown in Figure 1. The plot in Figure 1 is for the single measure of the narrowest nasopharyngeal opening in millimeters.

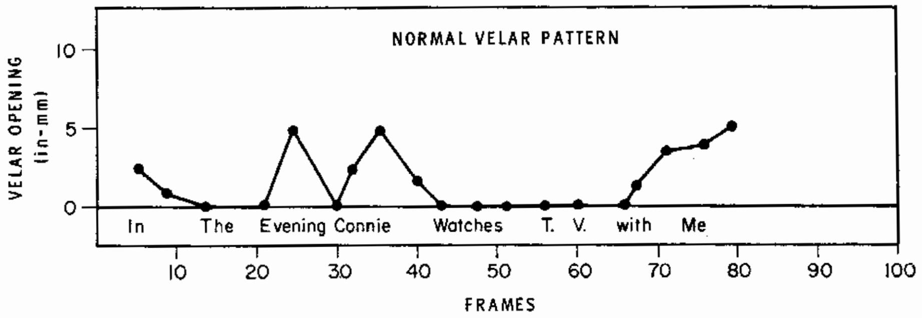

FIGURE 1. Plot of measurements of narrowest nasopharyngeal opening illustrating four open and three closure periods found for 100 normal-speaking adults on standard sentence.

The basic question of whether nonnasal speech can be produced without critical periods of complete velopharyngeal seal requires further study. It appears from x-ray studies of normal speakers that complete closure typically is found for certain definable portions of speech behavior. The conditions of phonation and loudness of voice which may affect the perception of hypernasal speech distortions under conditions of incomplete velopharyngeal closure need further study and consideration in interpreting the present limited information. The evidence available today from all assessment methods leads me to believe that complete closure of the velopharyngeal mechanism is indeed a requirement for nonnasal speech under conditions of clear and forceful phonation.

The Parameters of "Normal" Velopharyngeal Function

A large number of radiographic investigations have been carried out to define in detail the parameters such as height of the soft palate, area of contact, and amount of contact found in normal-speaking subjects under specific conditions of speaking. Further study is needed, particularly through development of a satisfactory method of visualizing lateral pharyngeal wall movement patterns in connected speech. Small discrepancies in the findings of past studies of the midsagittal parameters such as height of closure for normal-speaking adults are now explainable through the recent finding of significant basic differences between male and female subjects reported by McKerns and Bzoch (1970).

The high point on the velar surface seen in the closed or functional position of the velum for speech has been called "levator eminence." It has been defined as the point of insertion of the levator muscles (Green, 1961; Westlake and Rutherford, 1966, p. 61). Podvinec (1952) stated that the point at which the insertion of levators and of palatopharyngeus cross causes a "dimpling" seen on the oral surface of the velum. This point, according to Podvinec, becomes the center or focal point of the velar tissue which effects the closure and is in the area of greatest excursion from rest to closure. Figure 2 illustrates a midsagittal tracing of the velum in closure during speech similar to that which has been described and illustrated by Podvinec (1952), Ricketts (1954), Hagerty et al. (1958), and Green (1961). As it has been described in the foregoing papers, the uvula is angled forward.

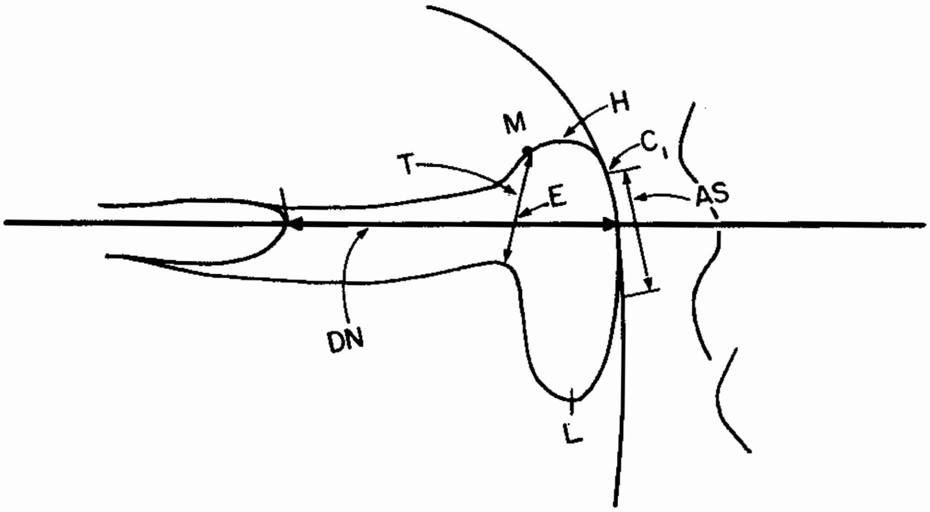

FIGURE 2. Line drawing of a cinefluorographic frame showing the seven measurements made in the study. L = Length of velum—measured from posterior point of hard palate around nasal surface of soft palate to midpoint of uvula. T = Thickness of velum—measured from midpoint of velum on nasal surface across the shortest distance of the velum on the oral surface. AS = Amount of seal—measured from superior and inferior points of contact of the velum and posterior pharyngeal wall. H = Height of velum—measured from the palatal plane to the highest point of the velum on the nasal surface. E = Elevation of velum—measured from the midpoint of the thickness measured perpendicular to the palatal plane. DN = Depth of nasopharynx—measured along the palatal plane from the posterior point of the hard palate to the posterior pharyngeal wall. C_1 = Superior point of velopharyngeal contact.

On the basis of observations made possible by the use of x ray, the area of the velum which makes closure was first defined as the middle third by Calnan (1955). However, when Graber, Bzoch, and Aoba (1959) divided the outline of the velum into quadrants rather than thirds they found that the third quadrant from the hard palate made closure contact in 100% of their young adult subjects. In 27% the fourth quadrant was also involved. The highest point on the upper surface (levator eminence) did not coincide with the area of contact, but was farther forward at the midpoint of the middle third of the soft palate. The midpoint of the palate showed the greatest extent of upward and backward movement. Ricketts (1954) pointed out the possibility that individual structural variations might account for small variations in these dimensions of the velopharyngeal closure.

Age and High Point of Closure

Calnan (1955) stated that the area just above the palatal plane would be the probable site of closure. He defined three possible relationships of the palatal plane to the back wall. The highest site, level with basisphenoid, was described as the "infantile" position for velopharyngeal closure. The adult position, Calnan said, was normally level with the upper border of the arch of the atlas or lower. Aram and Subtelny (1959) agreed with Calnan and stated further that the higher and more forward position for velopharyngeal closure in young children was due to the fact that the hard palate was closer to the upper limit of the nasopharynx. As growth of the face occurs downward and forward, the palate descends and the distance increases from the posterior pharyngeal wall, according to these authors. They described the site of closure for their younger groups as being "superior" and "in the superior-posterior aspects of the nasopharynx. Site of closure for the older groups was described as at the "posterior pharyngeal wall." The transition described took place mainly in their 9-to-11-year age groups.

However, Bjork and Nylen (1963) reported that the site of closure in children was actually lower than in their adult subjects. They stated that this was because of the greater forward inclination of the posterior wall in children as opposed to the almost vertical plane of the adult. The differences in these reports appear to be semantic rather than real, and may be due to different methods of measurement. Clearly, the physiologic differences between children and adults in functions of all the organs of speech need further definition and study through objective x-ray data.

Racial and Sex Differences

Hagerty et al. (1958) reported that there were some differences in the amount of excursion from rest to closure between black and white subjects. They also found some differences in the amount of contact of velum with pharynx in the two groups. To date, no systematic studies of racial differences in physiological functions of the organs of speech have been reported.

Mazaheri, Millard, and Erickson (1964) used 10 normal subjects as controls in a study of velopharyngeal inadequacy. They reported that they found the high point of closure for these normal subjects was below the palatal plane in 80% of their subjects. This finding was contrary to previous reports in the literature on normal subjects. In the Mazaheri, Millard, and Erickson study, 8 of the 10 control subjects were females but no significance was attached to this in interpreting the findings. Bjork (1961) and Bjork and Nylen (1963) had found no difference that was significant on the measurements they made between males and females. However, they measured only the amount of excursion, amount of contact, height of elevation, and the length in the rest position of the soft palate in their comparison. McKerns (1968) conducted a more detailed study to define differences in velopharyngeal functions between male and female adult subjects. She found significant basic differences between 20 male and 20 female adult subjects through cinefluoroscopic research techniques. The differences explain previous discrepancies in the literature and suggest leads for future studies. McKerns found:

1. Seventeen of 20 males had the inferior point of contact on (5) or above (12) the palatal plane while 17 or 20 females had this point below palatal plane.
2. The height of elevation of the soft palate was greater for males. The mean height of elevation above the palatal plane for males was 10.05 mm while for females it was 5.9 mm.
3. The mean amount of contact was 9.5 mm for females and only 5.7 mm for males.
4. The mean measurement of an angle ABC in males was 69.7° and for females it was 88.1°. With 79° defined as the upper limit for a male category as defined by angle ABC, and 80° the lower limit for a female category, 17 out of 20 of each sex were in their appropriate categories and 3 of each sex were in the category for the opposite sex. Angle ABC was determined by (A), the posterior nasal spine, to (B), the highest point of closure in the nasopharynx, to (C), the uvula.
5. Measurements demonstrated that the uvula is angled forward away from the posterior wall of the pharynx in males more than in females.
6. The sex differences found could not be related to differences in depth of the nasopharynx or length of the palate.

Further studies relating lingual, laryngeal, and palatal differences to coarticulation and rate differences between males and females are needed.

Adenoids, Passavant's Pad, and Forward and Lateral Movement of the Pharynx

Adenoid tissue can narrow the distance to be spanned so that where velopharyngeal inadequacy would otherwise be present, the problem may be avoided (Calnan, 1953; Buck, 1954; Subtelny and Koepp-Baker, 1956). However, further studies are needed which more clearly relate the effects of tonsillectomy and adenoidectomy to variations in velopharyngeal valving for speech.

Attention has been given to determining whether or not the action of Passavant's pad is significant in normal or abnormal velopharyngeal mechanisms. Calnan (1953 and 1955) had completely discounted it. However, Graber, Bzoch, and Aoba (1959) found a dramatic "Passavant's pad" activity in 4 of their 50 normal adult subjects. Cooper (1956), Warren and Hofmann (1961), and Bjork and Nylen (1963) say they have found no significant anterior movement of the posterior pharyngeal wall in normal subjects. Carpenter and Morris (1968) recently have illustrated differences in the Passavant pad functions found in six different cleft-palate subjects. Further x-ray studies appear needed in this area.

X-ray studies of lateral wall movements of the nasopharynx have been limited by technical problems to date. Researchers have theorized several muscle mechanisms underlying palatal and lateral pharyngeal wall movements which will have to be tested by combined x-ray, electromyographic, and fiberoptic studies. Bjork (1961) and Bjork and Nylen (1963) reported the results of analsis of tomography data used in their study to estimate the role of lateral movements of the pharyngeal wall in the nasopharynx. They asserted that there were no important changes in lateral dimensions in normals although they found lateral motion. In cases of velopharyngeal incompetence they reported considerably more motion which was compensatory, in their opinion.

Interrelationship of Velar Length and Pharyngeal Depth

Warren and Hofmann (1961) tried to determine possible relationships between velar length and pharyngeal depth, pharyngeal depth and velar height during closure, and velar length and velar height during closure. They concluded from cinefluorographic data that there were no predictable relationships. An inverse relationship was found between length of palate and height of closure. However, Mazaheri, Millard, and Erickson (1964) found a correlation between length of velum and depth of the pharynx. They found no significant relationship between depth of nasopharynx and height of elevation above palatal plane or between length of velum and height of closure.

Effects of Phonetic Variations on Velopharyngeal Function

Small variations in velar positions related to the production of different speech sounds have been studied. Bzoch (1960) reported finding no differences in velar height for the /p/, /b/, /t/, or /k/ sounds produced in CV syllables with the same vowel through cephalometric analysis. Hagerty et al. (1958) showed that elevation of the velum was higher for /s/ than for /a/ through analysis of data from lateral laminagraphs.

Moll (1960) reported a cinefluorographic study of velar changes in two female subjects in some detail in regard to the amount of velopharyngeal contact for different sounds. For vowels in consonant contexts, he found there was more contact when the consonant was a nonnasal than when it was the nasal sound /n/. Contact for /a/ was found to be less than for /i/. Moll (1962) showed that velar elevation was related to tongue height. Bzoch (1968) reported a cinefluorographic study of five normal subjects which showed that, in consonant vowel syllable productions of the sounds /i/, /a/, and /u/, the velum rises higher for /i/ and /u/ than for /a/ syllables.

A major research goal for clinical practice applications has been to define parameters as the expected site of velar contact along the pharyngeal wall, the height to which the velum elevates relative to palatal plane, the amount of tissue making contact, and whether there is a relationship of velar length to pharyngeal depth. This information is useful to clinicians responsible for physical management procedures in oral surgery and prosthetic appliances designed to cope effectively with rehabilitation problems caused by velopharyngeal insufficiency. However, these variables and the major factors such as age, race, and sex which affect them have not been fully considered in terms of the coarticulation patterns of velopharyngeal functions in normal speech in the studies to date.

Cinefluorographic studies reveal that the palate moves from its rest or relaxed (open) position to its functional or closed position as seen in lateral x-ray pictures usually before the first pressure consonant sound is articulated in the oral cavity. The palatal configuration resulting from the height to which it elevates, the place on the pharyngeal wall where it touches, the extent of contact, the area of its surface which makes the seal, and the position of the uvula relative to the posterior pharyngeal wall, changes only slightly in relation to the sounds being produced in connected speech utterances until a nasal consonant must be articulated. Then the velopharyngeal port must open and close again in coordinated movements with the lips or tongue. Openings of the nasopharynx will preceed nasal-sound oral articulations and the ending of most utterances. Moll and Shriver (1967) have raised the basic issue of whether the velum really functions as an articulator. They stated that the velum may act merely as an "on-off" valve. The valve would be "on" for nonnasal consonants and "off" for nasals. The more subtle adjustments of the velum reported through x-ray studies during speech could be due to changes in the restraints resulting from tongue position and the time available between on and off functions.

Lubker (1968) and Fritzel (1969) have reported separate electromyographic with cinefluorographic studies which do not support this theory of Moll and Shriver. The small variations in velopharyngeal valving observed through x-ray studies have value for developing testable theories of underlying neuromuscular mechanisms if further studies confirm that the velum functions as an articulator rather than a simple valve.

Velopharyngeal Coarticulation Patterns

Shelton (1964) defined six categories of closure patterns; that is, patterns of closing the gap between velum and pharynx and of maintaining appropriate closure. Speakers with no speech problems established a normal pattern similar to that reported by Bjork (1961) and Bzoch (1967). Deviations from this pattern were plotted for subjects who had palatal inadequacies or who had surgically repaired cleft palates.

Velopharyngeal Insufficiency

The problems of cleft-palate speakers have been studied through radiographic techniques in regard to several differences including tongue position (Hixon, 1949) and amount of mouth opening (Kelly, 1934). However, when Buck (1953) studied both of these factors and the factor of velopharyngeal insufficiency, he concluded that it was the extent of velopharyngeal closure which determined the major differences between his normal and cleft-palate subjects. The relative importance of other contributing factors has been studied by comparing cleft-palate subjects with each other (Bzoch, 1956; and Counihan, 1956). In addition, Powers (1960), using cinefluorographic techniques; Sloan et al. (1964), through cephalometric cinefluorography; and McWilliams, Musgrave, and Crozier (1968), through lateral still x-ray techniques, all concluded that if nasopharyngeal closure is not sustained, hypernasal speech distortion will occur.

The question of velopharyngeal inadequacy in the absence of cleft palate also has been studied for its effect on speech. Blackfield et al. (1962) reviewed the literature in which velopharyngeal dysfunction without cleft palate had been defined and described. In their x-ray study, they made measurements from tracings of cinefluorographic films of 24 noncleft patients with velopharyngeal dysfunction and compared them with 30 individuals with normal speech. Anatomic abnormalities found included excessive depth of the nasopharynx, short hard and soft palates, and short soft palate but normal hard palate and inadequacy of palatal motion. They concluded that, with the exception of two patients, there was clear x-ray evidence of a direct relationship between the degree of inadequacy of velopharyngeal closure and the severity of the speech defects.

Williams, Bzoch, and Aggee (1967) reported that the coarticulation pattern they found for velopharyngeal closure in connected speech for 100 normal subjects was not achieved by any of 18 deaf oral speakers or by any of 20 cleft-palate patients with hypernasal speech. Hypernasality in the cleft-palate speakers resulted from the inability to achieve any velopharyngeal closure as in the velopharyngeal closure pattern plotted in Figure 3. In addition, the inability or functional failure to sustain appropriate timing rates of opening and closing the velopharyngeal port, as demonstrated in Figure 4, also correlated with judgments of hypernasality. The radiographic findings demonstrated by patterns like that in Figure 3 were interpreted as clear evidence of organic velopharyngeal insufficiency for clear speech, requiring physical management through pharyngeal flap or other surgery or through prosthetic speech appliances. The velopharyngeal insufficiencies (as in Figure 4) which reveal potential for some complete closure were interpreted as indicating a need for a trial period of diagnostic speech therapy. Direct velar muscle training and oral-nasal speech exercise techniques to improve velopharyngeal function for speech were tried in such cases before proceeding with physical management.

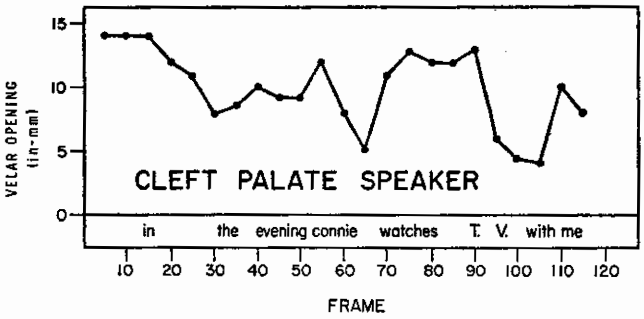

FIGURE 3. Plot of measurements of narrowest nasopharyngeal opening illustrating organic velopharyngeal insufficiency for cleft-palate speaker on standard sentence.

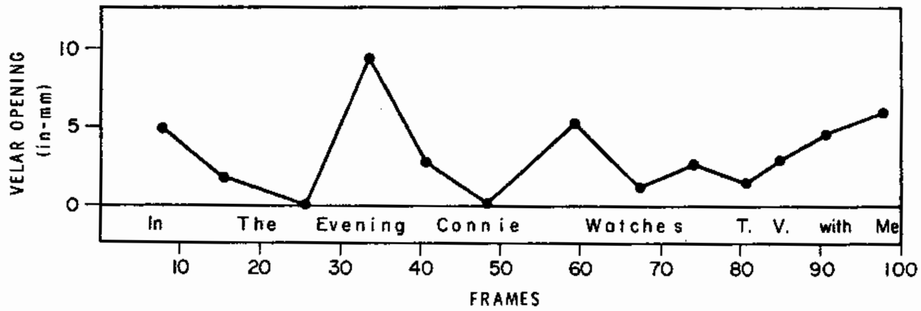

FIGURE 4. Plot of measurements of narrowest nasopharyngeal opening illustrating potential for complete closure and possible functional velopharyngeal insufficiency for cleft-palate speaker on standard sentence.

Figure 5 demonstrates the type of functional velopharyngeal insufficiency demonstrated by all of 18 adult deaf-oral speakers. The coarticulation pattern of velopharyngeal functions demonstrated in this figure is similar to that in Figure 4 but differs in overall duration (rate) and by frequent evidence of closure during nasal-sound articulation. Both hyponasal and hypernasal distortions of speech resulted within the same utterances. The determination of organic or functional forms of velopharyngeal insufficiency from radiographic evidence of this nature could provide an objective method for future clinical research studies and needs further reliability and verification investigations.

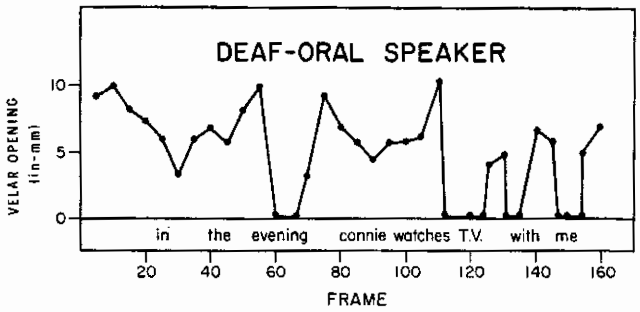

FIGURE 5. Plot of measurements of narrowest nasopharyngeal opening illustrating functional-coarticulation velopharyngeal insufficiency demonstrated by each of 18 adult deaf-oral speakers on standard sentence.

SOME PROFITABLE AREAS FOR FUTURE RESEARCH

This review of the literature on applications of radiographic research of importance to dentistry and speech pathology indicates that there are many important areas for present-day and future applications of this method of scientific investigation. Investigators in both fields should be able to avoid the pitfalls of past radiographic studies conducted without careful controls or interpreted without consideration of the many major, independent variables defined in previous research. The use of new, refined radiographic tools available today could add important further basic information regarding the interrelationships of structure and functions of the oral-facial complex.

Some specific promising areas for future investigations include:

1. Comparative studies of compensatory speech articulation and other oral functions in groups of subjects with different occlusal and dental abnormalities.
2. Specific studies of the compensatory articulation functions related to the insertion of prosthetic or orthodontic appliances in the mouth.
3. Description in detail of the compensatory coarticulation which follows various forms of oral surgery.
4. Descriptive studies of physiological parameters of functional speech disorders such as the articulation-substitution of pharyngeal fricatives for oral fricatives.
5. The development of techniques to distinguish between disorders with organic and those with functional etiologies.
6. Applications of the refined laminagraphy techniques to study functions such as the lateral wall movement in the nasal pharynx.
7. Studies of individual patients with structural abnormalities including severe malocclusions, to analyze satisfactory methods of compensatory articulation.
8. New studies of the physiologic parameters involved in oral functions of individuals who can produce varying voice and speech patterns and of functions such as ventriloquism.

9. Methodological studies to perfect automatic data extraction, and storage and retrieval systems for data derived from radiographic methods of investigation.
10. Before-and-after studies of the effects of tongue-thrust therapy and the use of appliances for modification of tongue thrust.
11. Refined studies of coarticulation processes in normal speech, including the interrelationships between laryngeal, lingual, pharyngeal, velar, oral, and labial functions in process.
12. The application of combined-methodology studies to specify the interrelationships between airflow, acoustic energy, and physiological coarticulation functions in larger groups of defined normal and abnormal subjects.

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PHYSIOLOGICAL MEASURES OF SPEECH MOVEMENTS: EMG AND FIBEROPTIC STUDIES

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Since the topics discussed in this *Report* are divided in a fashion which is reasonable from the point of view of labor-sharing, but not from the point of view of orderly theoretical exposition, I shall begin by making a distinction between the nature of the data obtained from fiberoptic and transillumination studies, on the one hand, and electromyographic studies, on the other. Although both these techniques are useful in discussions of the orofacial functioning other than speech, the speech area is the one that I know best, and, consequently, I shall make no attempt to review the extensive literature on the use of electromyography in the study of chewing, for example.

Detailed studies of speech articulation have suffered in the past from the general inacessibility of the speech mechanism to direct viewing. A number of techniques have been developed with vastly different technologies, which share the same object—that is, the observation of the movement of the articulator in space and time. Although the technologies are different, the end result will be the same, except for differences due to distortions or incompleteness of the view given. For example, we find Lindblom (1968) and MacNeilage (1969) using light monitors to describe the position of the lip and jaw. Other workers, Houde (1969), for example, have used x ray for essentially the same purpose.

One of the techniques I shall discuss, fiberoptics, is one of the group of techniques for viewing the movement of articulators—in this case, the larynx and its associated structures. Other techniques, such as x ray, indirect laryngoscopy, and observations of patients who have had massive surgical removals in the orofacial area may supply the same information. Electromyography, the second technique to be discussed, monitors an entirely different level of function, that is, the signals which accompany muscle contraction and lead to the movement of the articulators.

This review will be divided into three parts: first, current techniques in fiberscopy and transillumination; second, the status of the electromyographic technique; and third, the circumstances in which EMG seems particularly useful. Findings from each technique will not be reviewed; the primary purpose of the paper is to indicate where the techniques might be employed usefully.

FIBEROPTIC OBSERVATION OF THE LARYNX

In this section, I will rely heavily on the work of my colleague, Masayuki Sawashima, now visiting the Haskins Laboratories from the Institute of Logopedics and Phoniatrics of Tokyo University. Fiberoptic techniques appear to have been used in speech research only for observation of the larynx although there is no reason in theory why modifications of this technique could not be used for other purposes, such as observations of velopharyngeal closure.

Several techniques have been used in the past for observation of the larynx. Indirect laryngoscopy has been in use since the 19th century. Under ideal circumstances, excellent movies can be made of the opening and closing of the larynx during production of sustained vowels. (See Lieberman, 1961, for example, or Timcke, von Leden, and Moore, 1958.) The difficulties with the method are, however, that good mirror viewing requires suitable anatomy and a low gag reflex in the subject. A more serious objection is that observation of the larynx is not possible during running speech. The Taub panendoscope (1966) is essentially a useful modification of classic technique, and suffers from the same limitations.

Techniques have been developed which overcome this limitation of observation. Transillumination of the larynx has been used by various investigators, including Sonesson (1960), Moore,[1] and Lisker, Abramson, Cooper, and Schvey (1969). The principle involved is to put a light source on one side of the larynx, and a photocell on the other. The light transmitted will be roughly proportional to the glottal area. Since the light source can be made less bulky than the mirrors used in classic indirect laryngoscopy, it is possible to insert the light through the nasopharynx and obtain a record of the overall size of the laryngeal opening in running speech. Its disadvantage is that it does not record the shape of the glottal opening, but merely the area. Consequently, one cannot make good inferences about the precise detail of the opening and closing mechanism.

With the development of fiberoptic systems, it has been possible to combine the true image properties of indirect laryngoscopy with the continuous viewing advantage of transillumination. The fiberscope depends for its operation on the fact that a long cylinder of glass can transmit light from one end to the other. If the light-transmitting cylinder is bent into a curve, there will be only moderate leakage, which can be minimized by coating the fibers. Modern technology has made it possible to produce extremely thin filaments of glass, of diameters of only a few microns. In such sizes, glass fibers are extremely flexible. Consequently, it becames possible to use bundles of such fibers to transmit an optical image over a tortuous pathway, such as that from the larynx out the nasal passage.

Optic bundles have been used widely in various medical applications, such as a flexible gastroscope. Sawashima has developed a practical working fiberscope for laryngoscopic use (Sawashima et al., 1968). This device now is avail-

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[1] Moore, P., personal communication (1969).

able commercially.[2] The fiberscope consists of a hard tip, a flexible optical cable, an optical connector, a light source, and a camera. The tip of the fiberscope is approximately 6 mm in diameter, and consequently can be inserted easily through the nasal cavity of most subjects without discomfort. We do, however, anesthetize the nasal fossa and epipharynx with a 4% Xylocaine (lidocaine) solution.

Excellent still photographs or movie sequences can be made with an appropriate camera tied in to this device. The only problems that arise seem to be rather minor. The first, and more important, is that the larynx moves not only open and closed, but also up and down and in some more complex rotational patterns, while the fiberscope moves simultaneously. Consequently, the relationship of the fiberscope tip and the glottal chink cannot be fixed.

The image of the glottal chink occasionally moves out of the viewing field or varies in how well it is focussed. Also, since the distance varies, the size of the image is not in constant proportion to the size of the opening, nor is it always in focus. Later models of the fiberscope have an external repositioning device which sometimes is helpful in keeping the image in the field, but doesn't help with the other movement artifacts. A second problem is that the image is not as bright as would be desirable for all purposes. The light source, however, probably can be improved.

This device should have wide experimental and clinical application. It has already been a useful source of information in studying the opening and closing of the glottis for stop consonants (Lisker et al., 1969). It probably can be used as a routine tool for clinical laryngeal examination. As was suggested earlier, it probably could be used with slight modification for observing velopharyngeal closure; an extremely similar bronchoscope already has been manufactured.

ELECTROMYOGRAPHIC RECORDING

In this section, I shall rely heavily on two earlier reports on the technology of electromyographic recording—an earlier one by Cooper (1965) and a later one by Gay and Harris (in press). In this section, reemphasis will be placed on the two technical problems most troublesome to investigators in this area—the probe used for picking up potentials, and the type of analysis used in processing them. Other problems generally have been solved adequately in ordinary commercial EMG installations.

Electromyography is a technique for providing graphic information about the time course of the electrical activity which accompanies muscle contraction. All muscles consist of large numbers of fibers arranged usually in parallel inside a sheath. Groups of fibers within the muscle are connected to a single neuron, and contract when signalled by that nerve fiber. The size of the ratio between the muscle fibers and the nerve fiber varies among the skeletal muscles, with the

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[2] Inquiries may be addressed to The Olympus Corporation of America, Medical Instrument Division, 2 Nevada Drive, New Hyde Park, New York.

ratio relatively small for the muscles of skilled movement, such as those for speech. When a neural impulse arrives at the motor end plate, the region of connection between muscle and nerve, a wave of depolarization sweeps along the associated muscle fibers, and accompanies their contraction. If two wires are placed with their exposed ends close to each other and to the muscle fiber, momentary differences in the electrical potential at the wires can be observed when the muscle contracts; their magnitude will depend on the distance of the wires from the site of activity. As the strength of contraction increases, there will be recordings from more units in a fixed time interval. The details of the appearance of the electromyographic record under various clinical conditions are summarized in standard texts on the subject.

The electromyographic system, then, will consist of some sort of probe for picking up the potentials, amplifying equipment, recording equipment, and an ultimate graphic display, which may have more or less signal processing equipment incorporated. I shall discuss some problems connected with the type of probe, and with the ultimate display.

In speech research, three types of probe have most generally been used—surface suction electrodes (Harris et al., 1964), conventional needle electrodes (Buchthal, 1957), and so-called "hook" electrodes (Shipp, Deatsch, and Robertson, 1968; Hirano and Ohala, 1969). All three electrodes record essentially the same information; the differences between them depend simply on the distance between the probe and the site of activity, and the size of the probe. Generally, the larger the probe, the more units it will record from. The further the probe from the activity, the more units it sums, and the smaller the activity. (Distance probably will also affect the frequency characteristics of the signal, but no use has been made of these properties thus far.)

The choice among probe types seems to be largely a matter of convenience for the problem at hand. Useful work has been done with all three. The surface suction electrode we use at Haskins Laboratories has been described exhaustively in the reference just cited. It is useful when the articulatory movement of interest is caused by a muscle close to an orofacial surface. For example, a number of investigators have used it to investigate lip closure in labial consonant formation (Harris, Lysaught, and Schvey, 1965; Fromkin, 1966; Tatham and Morton, 1969), and levator palatini action in velopharyngeal closure (Harris, Schvey, and Lysaught, 1962; Lubker, 1967). In both cases, the gesture studied is rather unambiguously related to a single muscle. A second advantage of the surface electrode is that it is a less drastic procedure than inserting a hook or a needle; it can be used by speech researchers without medical help, or in clinical circumstances, such as the office examination of a small child, where minimum trauma is desirable. The disadvantage is that many speech events take place in muscles far from an appropriate electrode site.

The needle electrode can be inserted into virtually any articulatory muscle. Most of the early work on the laryngeal muscles was done with needle electrodes (Faaborg-Anderson, 1957, for example). The particular advantage of the needle electrode is that it is available commercially, and has a long history of use in a large clinical literature. Its disadvantage in speech research is that many of the articulators are small and change shape rapidly. Therefore, the electrode is dislodged easily during a long recording session, and may be quite painful.

These disadvantages are overcome by the use of hooked wire electrodes, now in use by several groups (Shipp, Deatsch, and Robertson, 1968; Hirano and Ohala, 1969; Fritzell, 1969). Apparently, Basmajian and Stecko(1962) first developed the technique. The electrode consists of a thin wire threaded through the cannula of a hypodermic needle. The exposed end of the wire is bent back over the needle to form a hook. The needle is used only to carry the wire electrode to the desired location, after which it is withdrawn. Upon withdrawal of the needle, the hooked portion of the wire becomes anchored in the muscle.

The disadvantages of the hooked wire procedures are two: first, small adjustments in the electrode position cannot be made once the needle is inserted; second, as hooks are presently constructed, the distance between the two hooks is variable and not under the experimenter's control. We are presently investigating the possibility of using an insulated double-stranded wire instead of the present two separate strands.

No matter what the electrode type, it may be worth pointing out that it is almost impossible for a researcher to be entirely satisfied on either of two fundamental points—first, that he is in fact recording from a given, "named" muscle, identified by reference to an anatomy text; second, that the amount of activity recorded is directly proportional to the contraction of that muscle. There are several reasons for this. As to muscle name, it is well known that human anatomy is quite variable. Certain muscles, such as the facial fibers, may differ considerably in their arrangement from one individual to another. In view of such peculiarities, it is not always clear what fibers are picked up if an electrode is inserted carefully according to a formula.

The only solution to this problem seems to lie in more extensive anatomical studies of the entire orofacial region, particularly of muscle and nerve structures, to accompany the work on skeletal structures described by Hixon in this *Report*. At the present, one is frequently in the position, in electromyographic research, of localizing a given muscle by its apparent function, and then, in turn, describing the function as if the localization were made independently. It is not clear, either, what the orientation of the firing fibers will be relative to the electrode. Hence, a demonstration such as Rosenfalck's (1960)—that the relationship between measured activity and muscular contraction may not be generalizable to any particular situation; that is, more measured activity will probably result in more movement, but the relationship is not necessarily linear.

Furthermore, there is a conflict between the choice of electrodes for minimum crosstalk and appropriate sampling size. As Dedo and Hall (1969) recently have pointed out, the type of unipolar concentric needle electrodes often used in the past in laryngeal research will pick up significant amounts of firing from muscles adjacent to the intended signal source. They suggest the use of bipolar concentric needle electrodes, or "paired" platinum wire electrodes for laryngeal work. However, this advantage is bought at the expense of making a very small sample of the firing units in the muscle, which carries its own disadvantages, as I shall show. Probably there should be an adjustment of probe size to muscle size and geometry, but here, again, there is serious need of better anatomical work for the entire region.

In this discussion, we will leave aside the more general problems of amplifying and recording equipment, which are adequately discussed in more general texts, and pass on to the general problem of processing EMG data for display. The simplest display is some sort of direct representation of the amplified and recorded muscle signal against a representation of the acoustic speech signal. Such displays have been used effectively for qualitative arguments, but are not easily quantified; individual samples of a given utterance are quite variable. There are three obvious reasons for this. First, the display represents a signal from many individual unit spike potentials, which are random in phase. Consequently, one expects random fluctuations in size. Second, a given electrode picks up only a small sample of the firing units in a given muscle, and the smaller the electrode, the smaller the sample, and presumably, the larger the sampling error from purely statistical considerations. Third, there are fortuitous differences in the articulatory movement for a given speech sample. All these three considerations suggest that observations should be averaged by some means.

The steps in this process used at Haskins are described by Cooper (1965), and Gay and Harris (in press). Here I shall make only general remarks about the procedure. First, the signal is full-wave rectified. (Otherwise, positive and negative fluctuations of the signal could cancel each other out.) Then it is sent through an integrating circuit, and a number of tokens of the same utterance are averaged. The smoothness of the resulting averaged utterance depends both on the time constant of the integrating circuit and on the number of the included tokens. In our experiments, we usually average about 20 tokens, and choose about a 20-msec time constant for the integrating circuit.

This choice of a 20-msec time constant means that an instantaneous decrease in activity will take 20 msec to decrease to 67% of previous value. If the time constant is made longer, there will be increased probability that rapid changes in the signal will be time-smeared in the output data; if the subject is kept repeating the same utterance too long, he may change his articulatory mode.

A final variable to be discussed is the lineup of different utterances for averaging. At present, an acoustic reference point such as the onset or offset of voicing is chosen arbitrarily, and averaging is performed at time samples anchored to that point. The trouble with this procedure is that if articulatory rate varies from sample to sample, there will be a tendency for events distant to the lineup point to be time-smeared; a preferable system would be to anchor at several acoustic events, and to time-normalize between.

Ohman (1966) has suggested such a procedure. He also has made use of a more complex procedure in which the EMG traces of each sample utterance, after rectification and integration, are matched visually for all prominent humps and dips, and averaging is performed with respect to these points. This technique seems theoretically impeccable, but does involve a large amount of experimenter intervention.

Several other research groups are working with setups similar to our own. The Tokyo group (Hirose, Kiritani, and Shibata, 1968) uses a similar recording setup, a 10-msec time constant, and averages with a PDP-9 computer. The University of California group (Harshman and Ladefoged, 1967) uses a somewhat different procedure. Utterances are lined up with respect to a single point, the "triggering point," apparently usually in some fixed time relationship to the onset of voicing in the utterance. The analogue signal is digitized, rectified, and applied to an integrator, which discharges at fixed intervals. Analogous time points are added appropriately to a running average. The output curve then is smoothed by repeated averaging of adjacent points. More of the time-smearing thus occurs in the smoothing, rather than in processing the original signal. It is hard to know what the effects of this procedure are, compared to those in our own program. The details of the programming scheme of the Exeter group (Tatham and his coworkers) have not been published yet.

The purpose of this whole section on the technology of EMG is not to enable anyone to build a system, but simply to indicate the extent to which the data in the literature at present have been conditioned by some choices of the experimenters, without any particular standardization, and frequently without any theoretically compelling reasons for making one choice over another.

THE USES OF ELECTROMYOGRAPHIC DATA IN SPEECH RESEARCH

In the introduction, I tried to indicate the ways in which electromyographic signals represented a level of functioning different from that shown by direct observation techniques, like x-ray studies and fiberoptic or acoustic studies. Ultimately, perhaps it may be taken as a matter of faith that speech is so important that all knowledge about the transformation of the speech signal from the cortex of the speaker to the cortex of the listener is important. This is, however, too general an article of faith to be helpful in deciding which problems to tackle now. There are some cases where it doesn't matter; information is needed about the laryngeal mechanisms for pitch control by any convenient means. However, there are some problems where electromyography seems to me to be the method of choice. These examples do not constitute a compendium of all interesting speech research using EMG technique. The work done has been too scattered to be sensibly presented in this fashion. I shall assume that the reader is using other sources for a detailed description of the articulatory muscles.

Suitable problems for EMG research will be divided into three classes—not that they are really mutually exclusive, but it will make discussion easier: first, "which muscle" problems; second, "which mechanism" problems; and third, a more vaguely defined class of problems having to do with the general organization of the speech mechanism.

"Which Muscle" Problems

In some cases, we have enough interest in a practical anatomical problem that the exact identity of the muscle controlling a particular articulatory act is important. This identity is not necessarily obvious from anatomy alone; individual differences in organization are common, as we mentioned above, and good anatomical studies, particularly of the tongue, are scarce. More important, as Hiki (1969) has pointed out with particular reference to the tongue, any one of several muscles sometimes may be presumed to have the same effect from geometric considerations.

A few examples will suffice. The function of the various muscles surrounding the velopharyngeal port has long been a subject of controversy. In particular dispute is whether the tensor does (Calnan's [1953] point of view) or does not (Rich's [1920] point of view) contribute, with the levator, to palatal elevation. In an elegant series of experiments, Fritzell (1969) showed that the tensor showed no consistent activity pattern in speech. He came to the practically useful conclusion that its anatomical action is not likely to affect speech. Whether his data justified the conclusion is open to question; the important point is that there is a practical consequence of the use of EMG technique.

A second area where specific muscle function is of interest is the pitch-control mechanism of the larynx. It is well known that the cricothyroid muscle acts to raise pitch, but it is not known whether the vocalis functions in parallel with it. Indeed, Luchsinger and Arnold (1965) have suggested that the cricothyroid is responsible for gross adjustments in pitch, while the vocalis makes fine adjustments. Recent work by Sawashima, Gay, and Harris (1969) confirms earlier work by Faaborg-Anderson (1957) showing that the gross activity of the vocalis increases with rises in pitch. Furthermore, the more recent work shows that the function relating cricothyroid and pitch increase is no steeper than that relating vocalis activity to pitch. However, there do seem to be individual differences which presently cannot be related to any other variables, due to the scantiness of the data.

Probably more interesting from a general theoretical point of view is the now classic study of Ladefoged and his associates (1962) on the action of the external and internal intercostals in syllabification. Stetson (1951) had erected a theory which suggested, in essence, that the syllable had a physiological basis, in that each syllable was initiated by an action pulse from the internal intercostals, and arrested by a pulse from the external intercostals.

Recording from the intercostals as well as from the other respiratory muscles, Ladefoged was able to show, first, that there is no simple pulse in either of these muscles that is associated consistently with syllabification. Beyond, and more important than, this negative conclusion, was the demonstration of the correlation between the action of all the respiratory muscles and the overall course of pressure events in the lungs. In the course of a single utterance, the pressures leading to the collapse of the lungs are high at the beginning, and the inspiratory muscles, including the external intercostals, are used to brake the outflow of air. On the other hand, at the end of an utterance, air must be pressed actively out of the lungs; and the expiratory muscles, including the internal intercostals, are active then. Thus, in this instance, an examination of a muscle identity problem has aided in the clarification of the whole speech respiratory function.

"Which Mechanism" Problems

In some cases, electromyographic study enables one to establish, or at least to limit, the function of muscular action in executing a particular articulatory maneuver. In the first two cases cited, there is a question as to whether a pair of opposing movements are both muscularly controlled, or whether one of the pair is merely passive.

The first example is from Fritzell's monograph on the action of the velopharyngeal muscles in speech (Fritzell, 1969). Again, it is quite clear that the chief agent of velopharyngeal closure in speech is the levator muscle. However, the muscle which appears to oppose it on anatomical grounds, the palatoglossus, is a small muscle, and often damaged during tonsil removal. It has been suggested, therefore, that the velopharyngeal port may be opened for the nasal sounds simply by the action of gravity plus the cessation of levator activity. Simultaneous EMG recordings of levator and palatoglossus muscle, however, show clearly that the latter is active in the transition from oral to nasal sounds. This leaves the question of why a tonsillectomy which damages the faucial pillars does not have more drastic effects on speech. Fritzell suggests that the palatopharyngeus may take over the function of the palatoglossus in these cases, but obviously, further work is needed.

A second, similar, problem arises in studying the action of the laryngeal muscles in pitch control. The cricothyroid and vocalis muscles both are active in pitch raising; one question at issue is whether there is an active muscular pitch-lowering mechanism. Lieberman (1967) has suggested that the pitch fall at the end of simple declarative sentences may be an effect of the fall in subglottal air pressure. However, certain features of sentence stress (Chomsky and Halle, 1969) and certain types of accent features seem to suggest that there is some specific mechanism for rapid pitch lowering which opposes the pitch-raising mechanism of the cricothyroid group. Ohala, Hirano, and Vennard (1968) have suggested that the sternohyoid may serve this purpose, apparently in part because Hirano, Koike, and von Leden (1967) have shown that the sternohyoid is active both at high and at low pitch extremes. Some preliminary work by Garding[3] and Ohala and Hirose (1969) suggests that, in speech, sternohyoid activity is connected both with jaw opening and with pitch lowering. No one

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[3] Garding, E., personal communication (1969).

seems to have demonstrated finally the mechanism for active pitch lowering. It may be that pitch lowering takes place when the muscles which actively raise pitch are inactive.

Organization of the Speech Mechanism

This topic is a rather general one, relative to the two preceding topics. Indeed, the experiments cited are really only very preliminary looks at very large questions. However, the questions themselves suggest ways electromyographic data may be used in discussions of the organization of speech behavior.

The first example is drawn from what Dorothy Huntington has called "experimental speech pathology." Experienced pathologists are aware that people with different pathologies sound unlike each other, but it is frequently difficult to characterize these differences except by rather vague subjective terms. Thus, deaf speakers are sometimes described as having "deaf voice quality" and so forth. The reason for this is, in part, that while it is easy to identify correct productions perceptually, it is much harder to say in articulatory terms what is wrong with a production which sounds grossly abnormal. Electromyography may help us to specify the dimensions of abnormality. For example, Huntington and I (with Sholes, 1968) studied the production of a few congenitally deaf speakers. As Calvert (1961) and others had previously noted, their articulation was abnormally slow. What was striking, however, was that their productions of visible consonants were grossly similar to normal, while their productions of nonvisible consonants were far more eccentric. Moreover, the productions of all consonants were as stereotyped and invariant as normal. That is, the deaf speakers appeared to have a normal articulatory habit, even when it was the wrong habit. By contrast, Shankweiler and I (1968) examined the articulation of some dysarthric speakers. The EMG signals we saw were both weak and highly variable—that is, their articulation was not stereotyped. While neither of these studies is anything but extremely preliminary, they show the ways electromyographic data might be used to characterize and contrast speech pathologies.

A final example indicated some ways that electromyographic studies can be used to clarify the role of sensory feedback in articulation, a question which has preoccupied several authors in this *Report.* Several years ago, Ringel and Steer (1963) published a study in which they examined articulation before and after mandibular block of the tongue. They found articulation was poorer after the block, and attributed the deterioration to the lack of sensory feedback from the tongue articulators. A student of mine, Gloria Borden, did an EMG study to determine the precise nature of the deterioration. We expected to find articulatory variability, or incoordination of the various muscles, particularly those involved in tongue-tip manipulation. We found that the coordination of most of the muscles we examined was perfectly normal following the block, but the mylohyoid appeared to be paralyzed. Apparently it was possible that anesthetic could leak from the mandibular foramen onto the mylohyoid nerve, which runs behind the space. The observation has been made only once, and must be repeated; but at the moment, we are not at all convinced that the Ringel-Steer phenomenon is sensory.

Let me conclude the discussion of this random assortment of experiments by repeating what was said at the beginning of the paper—electromyographic research is not simply a substitute for direct-viewing techniques. Instead, it carries us one step farther back in the chain of speech events that leads from the higher nervous system of the speaker to that of the listener. We hope that, in the years ahead, it will be another useful tool in the difficult task of breaking the speech code.

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ARTICULATORY ASSESSMENT

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The process of articulation can be considered from at least three points of view, namely, physiological, acoustical, and perceptual. The first of these entails the study of the movement patterns and valving systems of the vocal structures, the process whereby vocal utterances are produced. The acoustical approach pertains to the identification of the physical spectra of speech. In perceptual considerations, one attempts to study the phonemic and linguistic elements of speech. These three approaches are interrelated and not independent. Specifically, a listener responds to the phonemic code of a speaker (a perceptual task) by means of the physical characteristics of the signal (an acoustic property), which are determined by the positions and movements of the speaker's articulators (a physiological feature). The assessment of articulation likewise can be approached from these three directions. If assessment is thought of as a process of estimation, measurement, or specification, then certainly assessment would apply to the physiological, acoustical, and perceptual correlates of articulation.

There can be several motives for assessing articulation. The examiner may wish to determine simply whether a speaker has defective articulatory skills. That is, the purpose might be to identify those speakers with abnormal articulation, which usually involves some type of screening test. This purpose leads to a second objective of articulatory assessment. Once the speaker has been identified as having inadequate articulation, the examiner may desire a more complete specification of the pattern of articulatory errors, that is, a designation of which sound elements are in error and the regularity with which the errors are made. Traditionally, these are the usual functions of articulatory assessment, but the examiner might also devise an assessment technique which would tell him the etiology of the speaker's defective articulation. Presumably, the latter function would require at least an assessment of the physiological characteristics of articulation, whereas any test procedure whose purpose is a judgment of defectiveness inevitably requires a perceptual task.

Generally, however, the concept of articulatory assessment usually refers specifically to the perceptual system. An evaluator (a listener), on the basis of a speech sample from the speaker, determines the adequacy of the speaker to produce the phonemic code of the language. There are a number of ways for the listener to make this judgment, but the critical point is that it is a judgment process and that the judgment is made outside the speaker by the behavior of an auditor (Siegel, 1962; Tiffany and Bennett, 1968). In the case of cleft palate management, one of the most important objectives is "good speech." Since the concept of good speech really can be defined or determined only by the biases and standards of a human listener, articulation testing by the perceptual process of listening is the primary and basic means of assessment.

In studying articulatory assessment from the perceptual point of view, one must consider the nature of the listener's task. For instance, what is the most meaningful way of having the evaluator make his judgment? In addition, who is the best evaluator: a person highly trained in phonetics or the average unsophisticated listener competent with the language? What is the best type of speech sample to be used for the judgments, and how should this sample be elicited from the speaker? I will attempt to review in this paper some of the relevant literature on each of these issues and others as well. Also, I will allude to considerations as to how well the existent articulation tests fulfill the purposes of assessment mentioned earlier.

PICTURE ARTICULATION TESTS

Traditionally, at least for the assessment of articulation of children, a series of pictures is shown to the speaker, and he is instructed to name each of the depicted stimuli. Through this procedure, structured and specified oral responses are thereby produced so that the examiner can ascertain the adequacy of the speaker's articulation skills. As the child names each depicted stimulus item, the examiner listens critically to the child's production of the speech sounds being tested. He then indicates on a response sheet some marking to identify the accuracy of the child's production of each sound. In other words, on the basis of the examiner's perceptual judgment of what constitutes "normal articulation," he places some type of symbol on the response sheet. If, in the judgment of the examiner, the child substitutes another sound for the intended one, then a phonemic symbol to represent the substituted sound is placed on the sheet. If, on the other hand, the examiner judges that the child has omitted the test sound, then a different mark is placed on the sheet. Clinicians also consider a third type of error category, referred to as a distortion. The concept of articulatory distortion will be discussed later in the paper.

A number of commercially published sets of pictures are available to the clinician (Goldman and Fristoe, 1969; Hejna, 1955; McDonald, 1964; Templin and Darley, 1960). Generally, in each of these materials, one picture is designed to be used for assessing a single speech sound in one position within a word. Almost universally, items are arranged to include test sounds in the initial, medial, and final positions of words. The authors of these picture sets rather arbitrarily instruct the examiner as to which sound element is tested with each picture. Some picture sets do not include stimulus pictures specifically meant to test vowel articulation, even though obviously every stimulus word contains at least one vowel sound. The usual rationale the authors give for not including specific vowel stimulus pictures seems to be that most children are presumed to be able to produce vowels correctly as contrasted to consonants.

These picture sets are called articulation tests, but actually they are simply stimulus pictures designed to evoke a particular word response from the child. If the use of the term *articulation test* is appropriate, it should refer to the evaluative process of the listener, not to the sets of pictures. As an analogy, certainly we would agree that a cookbook is not a test of one's cooking ability. The cookbook prompts someone to cook something; the test of his cooking skill comes from the behavior of the taster. The cookbook is comparable to the picture articulation test.

There is an inherent clinical appeal to the use of these so-called picture articulation tests or inventories for assessing the adequacy of a child's articulation skills. The examiner finds them to be an expedient tool since he can quickly obtain a sample of the child's speech with controlled elicitation of the desired sound elements. The stimulus pictures usually can be drawn to maintain the child's interest. Most consonants appear in at least some words that can be depicted and which are readily within the child's vocabulary level. However, authors of picture articulation inventories have difficulty in handling such sounds as /ð/ and /ʒ/, since there are few instances of simple words containing these particular sounds that can be depicted.

TEST ASSUMPTIONS

There are several assumptions behind the use of picture articulation inventories. Several of these assumptions are not necessarily satisfied. (1) The examiner presumes that a child's production of a specified sound on a particular stimulus word at the time that the picture articulation inventory is administered is a true reflection of his inclusive articulatory ability for that sound. (2) A further implication of the test procedure is that the results are applicable to other speech situations. Generally, articulatory assessment is done in an artificial testing context with a single adult examiner "confronting" the child; from this setting, the examiner suggests that similar articulatory results would be noted in other settings, as, for example, when the child is playing with his peers. (3) The responses from the child are single-word utterances, but often the premise is inferred that the articulation test results can be extended to spontaneous or conversational speech. (4) As mentioned earlier, speech sounds are assessed in the initial, medial, and final word positions. Obviously, this arrangement of stimulus items assumes that there is a phonetic rationale for testing in these three positions. (5) Furthermore, the examiner presumably is skillful in translating the perceived events of the speaker into some type of symbolic code, that is, the examiner is "good" in the use of the IPA. (6) This manner of articulation testing also presumes that ". . . speech is considered a sequence of discrete elements, one following another like beads on a string"

(Curtis, 1968, p. 1). The assumptions included in this paragraph will be discussed in detail throughout the paper.

PHONEME BOUNDARIES

Figure 1 is a schematic representation of what can be considered as an "articulatory space" for the two phonemes /θ/ and /s/. The irregular-shaped regions are the so-called phoneme boundaries of /θ/ and /s/. As long as a sound is produced "within the boundary," the listener will perceive the utterance as /s/ is the one case or /θ/ in the other, provided the listener is proficient in the use of the phonemic code. Although the diagram shows the boundaries as very explicit, in actuality these boundaries are extremely vague and indistinct. After all, the whole notion is an abstraction. Nevertheless, for purposes of illustration I will take certain obvious liberties.

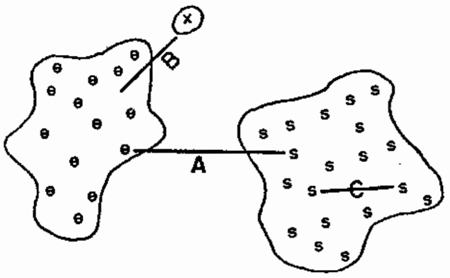

FIGURE 1. The "phonemic articulatory space" for /θ/ and /s/, showing three types of articulation errors.

The reason for showing several [s] and [θ] symbols within each space is to stress the point that a phoneme is made up of several phones. As Winitz states (1969, pp. 2-3), "Essentially an abstraction, the phoneme comprises a group or category of phonetic responses or phones; the phones are elements of the phoneme which do not characterize differences in word meaning." Although Winitz mentions that the phoneme is an abstraction, there is probably little argument that it is a behavioral reality defined as "a minimal unit of distinctive sound features—a finite set of mutually exclusive classes of speech sounds" (Berry, 1969, p. 443). The allophone, on the other hand, is "a phonetic term referring to the sounds that are classified as belonging to a particular phoneme, despite the differences among them detectable by the human ear" (Berry, 1969, p. 427).

Since the phoneme is an abstract way of defining a family of speech sounds, strictly it is not correct to say that a speaker produces a phoneme; he produces a phone. This paper is not the place to present a didactic exposition of the phoneme concept. The reader is directed to such sources as Chomsky and Halle (1968), Harms (1968), or Winitz (1969) for a more detailed linguistic description of the issue. In this paper I will consider the phoneme in its rather traditional usage as it typically appears in the speech pathology literature.

Line A in Figure 1 represents an instance in which a speaker makes a phonemic substitution of /θ/ for /s/. However, this substitution in fact may not occur for all instances of /s/. In other words, he may not, and probably does not, consistently make this substitution.

Upon careful and intensive testing, it may be observed that a logical pattern emerges in which the substitution is made for certain allophones and not for others. Basically, it appears that the phonetic context determines which allophone will occur. As an example, the [s] in *stop* is a different articulatory allophone from that which occurs in *sun* or in *bus*. However, the normal speaker will produce each of these allophones "within" the /s/ phoneme boundary, and the listener will perceive them all as /s/. The articulatory-defective speaker, on the other hand, may make an articulatory substitution of another phoneme for one or more of these allophones. Thus, the contextual influence of adjacent sounds determines which allophones are produced by the normal speaker, and may explain the patterns of inconsistency of the defective speaker in terms of linguistic regularity. Thus, he may substitute /θ/ for certain [s] allophones, omit other [s] allophones, and produce others correctly.

ARTICULATORY DISTORTIONS

Earlier in this paper, I mentioned that in describing types of articulatory errors clinicians generally use the categories of substitution, omission, and distortion. The notion of articulatory distortion needs some clarification. It is rather difficult to define the meaning of a distortion, but as Carrell (1968) states, it is "the substitution of a nonstandard rather than a standard sound for the one which would have been correct" (p. 15). The distortion may be perceived by the listener as the intended sound, but is recognized as being indistinct. That is, the error in this instance would fall "within the phoneme boundary" of the intended sound element, although it is clearly judged as being an incorrect phone. This noncanonical allophonic type of distortion is schematized in Figure 1 with line C. An example of such a distortion might be the lateralized [s].[1]

There are many instances, however, when an articulatory distortion is made in which the examiner cannot discern within which phoneme boundary the error occurs. We frequently observe articulatory errors that are extremely difficult to imitate or even for us to describe adequately. Figure 1 depicts this type of error. The *X* represents a distortion "outside" any phoneme boundary, inferring that listeners would be unable to agree as to the phoneme. However, in this instance the examiner probably would write on the response sheet that phoneme closest to the articulatory space occupied by the distortion. In the case of Figure 1, he would no doubt put down the symbol /θ/ as shown by line B, but clearly the production is not a "true /θ/ phoneme." Perhaps these types of distortions are responsible for many of the instances in which there is less than 100% agreement among examiners in tests of articulation.

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[1] In a personal communication, Winitz suggests that the concept of articulatory distortion is appropriate when a phonemic analysis is made but not when a phonetic analysis is made.

The problem of articulatory distortions is especially germane to the cleft-palate speaker who frequently exhibits nasal emission, glottal stops, pharyngeal fricatives, and so on. These error patterns create some difficulty for the examiner in deciding how to identify them on the response sheet or for his research data. Bzoch (1965) was aware of this, and handled them in the following manner:

> Specific substitutions of a glottal stop, a pharyngeal fricative, or a nasal snort for a test sound element were recorded as substitutions of sounds. . . . Sounds which were distorted by clearly audible nasal emission, but which close examination revealed were correctly articulated, were recorded as IE (indistinct due to emission) and were calculated separately from sounds which were judged to be indistinct due to faulty articulation of the lips and/or tongue. (p. 342)

Rather than simply grouping all articulatory distortions into the broad category of "distortion," it would seem valuable to identify the nature of the articulatory error as explicitly as possible. A phonetic rather than phonemic analysis of these sound errors would yield significantly greater information for the researcher and clinician. However, the phonetic analysis requires considerable sophistication on the part of the listener, which most examiners probably do not have.

As stated earlier, phoneme boundaries are in actuality extremely vague and indistinct. Perhaps the delineation of boundaries varies also according to the degree of phonetic skill of the listener. One who is adept at phonetic transcriptions may be much more proficient in assigning certain articulatory distortions to specified phoneme categories than is the less sophisticated listener. Speech pathologists may tend to assume that the assessment of articulation is equally as valid regardless of whether an experienced or inexperienced examiner is evaluating the speaker.

DYNAMIC CHARACTER OF SPEECH

During a vocal utterance, the articulators are in almost constant motion. From a physiological view, then, speech must be considered as a highly dynamic process: ongoing and ever-changing. The analogy I sometimes use is to regard the process of speech as a stream of flowing water from a hose. Perceptually, out of this changing flow the listener identifies discrete time events which he recognizes as the phonemes of the language. This perceptual process of assigning arbitrary or abstract events to the ongoing flow requires that the listener be competent with the phonemic code of the language. One merely needs to listen to someone speak a foreign language. He immediately is aware of the difficulty in identifying the speech sounds (the time events), and is impressed only with the ongoing flow.

We hear speech as a series of discrete events, but physiologically speech is not characterized as independent, separate elements in some time sequence of articulatory states (Curtis, 1968). The articulatory gesture influences, and is influenced by, other gestures. These contextual influences are called *combina-*

tory variants by Malmberg (1963) and *coarticulation* by others (Curtis, 1968; Daniloff and Moll, 1968; Oehman, 1966; Wickelgren, 1969). The interacting effects are observed in more than abutting, immediately adjacent sounds, since as Daniloff and Moll (1968) noted, coarticulation occurs across as many as four or five speech sounds.

In articulatory assessment, the examiner is applying his phonemic code to the speaker's vocal utterance, and thus he regards the response as a series of discrete events, like beads on a string. It follows that the property of coarticulation must be considered in the testing situation. There is little value in noting the production of speech sounds in isolation, and, furthermore, it is important to observe the child's articulatory behavior in many different phonetic contexts. McDonald's Deep Test of Articulation (1964) was designed with these matters in mind. He develops the concept of the syllable as a series of overlapping ballistic movements of the articulators, and assesses the child's ability to produce each sound in a variety of syllabic contexts. Although one might question McDonald's theoretical rationale and the fact that phoneme clusters are tested across word boundaries, he ought to be commended for developing a method of sampling articulation in a way which is quite different from the traditional approach.

TEST UNITS

From a psycholinguistic approach, the concept of a word is probably "a meaningful unit," but the concept has little phonetic validity, even though a word can be defined in phonologic terms (Osgood and Sebeok, 1965). According to Malmberg (1963, p. 70), "The word is a *semantic* unit and not a *phonetic* unit." There is extensive controversy in the literature as to what constitutes the basic articulatory unit of speech. Generally, the argument is concerned with whether the phone, syllable, or some larger structure is the building blocks of articulation. Oehman (1966), for example, suggests that " . . . the time unit of natural speech encoding is more of the size of a syllable than a phoneme." Certainly, however, any formulation of descriptive phonetics or phonology deals with articulatory specification at the phoneme level (Peterson and Shoup, 1966; Smalley, 1963). Be that as it may, the problem has relevance to considerations of articulatory assessment in the clinical diagnosis of deviant speech. Do we test articulatory ability at the sound or syllable level, or at some other, larger level? In order to observe the effects of coarticulation, as discussed earlier, tests of articulation should not deal exclusively with sounds in isolation. If the word is most likely not a meaningful articulatory unit, then measures of articulation based upon word units have little theoretical support. Furthermore, the common practice of testing sounds in the initial, medial, and final positions of words also would appear to have little validity. However, clinicians frequently encounter speakers who have mastered initial consonants fairly well and use them appropriately but who, for some reason, have not been able to acquire the entire word unit and are never heard to incorporate a final consonant. In some way, then, there is an interacting effect between phonetic and symbolic behavior. The speaker's articulation function would appear to be influenced by his habituated linguistic attitude.

DISTINCTIVE FEATURES AND PHONOLOGICAL RULES

The general field of linguistics has given the speech pathologists a possible frame of reference in understanding some of the patterns of articulatory functions. More specifically, the notion of phonological distinctive feature analysis can be helpful in explaining certain forms of articulatory errors. According to Berko and Brown (1960, p. 525), "The 'distinctive features' of an individual phoneme would be those aspects of the process of articulation and their acoustic consequences that serve to contrast one phoneme with others." For purposes of this paper, it is unnecessary to enumerate the phonemic features that authors have described (Jakobson, Fant, and Halle, 1952; Chomsky and Halle, 1968); suffice it to say that a series of binary contrasts appears to distinguish each phoneme of the language. Presumably, all allophonic variations within a phoneme boundary exhibit the same phonologic features, but according to Chomsky and Halle (1968), the distinctions between allophones are not binary contrasts but rather differences in level of each feature. The same, no doubt, holds true for coarticulation effects on sounds.

The articulatory assessment of a subject with defective speech may reveal that feature confusions exist. In other words, the articulatory errors may well be orderly and predictable if one does a feature analysis of the speaker's misarticulations. Menyuk (1968; with Anderson, 1969), for example, has used this point of view in studying the development of articulatory perception and production.

In any language there is presumably an abstract representation of phonological rules. As Stevens and Halle state (1967),

> . . . [a child] tries to establish the rules that govern the speech of its parents and utilizes these rules to construct utterances of its own. Since the child is new at it, he will occasionally fail to establish a rule correctly or he may overlook a rule altogether. . . . Viewed in this light . . . [certain articulatory errors are] no longer an inexplicable curiosity. (p. 95)

Applegate (1961) suggests the same type of situation. In other words, through extensive observation of the articulatory patterns of the speaker, we may conclude that incorrect phonological rules are being used, that they are being used out of sequence, or that certain rules are omitted. This type of analysis, of course, requires that the examiner be able to verbalize these rules. At the present time, we probably know implicitly what these rules are, but we do not yet know them explicitly. Linguists are attempting to clarify the representation of these rules, which should be of considerable value to the speech pathologist.

CONSONANT-VOWEL CONSIDERATIONS

Generally speaking, when one discusses articulatory assessment, he usually considers consonant rather than vowel production. I mentioned earlier that many picture articulation inventories do not include specific items for the assessment of vowel sounds since these typically are produced adequately by most speakers. There is some evidence that vowels and consonants are from an articulatory standpoint entirely distinct entities which involve differing muscular actions (Perkell, 1969). Logically, then, the examiner ought to separate these two classes of sounds in his interpretations of the speaker's pattern of articulation performance. The findings of Perkell give a rationale for understanding the speaker's articulatory behavior.

ADDITIONAL METHODS OF ARTICULATION TESTING

Means other than picture inventories are available to the clinician and the researcher to elicit desired responses. For older subjects, oral reading has had wide usage. A series of sentences or a passage is written that contains all of the desired test sounds (Fairbanks, 1960). There is some question, however, whether this approach yields a valid assessment of articulatory skills, since the subject may employ a different speech pattern in oral reading than he does in conversational, spontaneous speech. Some examiners will present a series of situational pictures to the subject with instructions to describe the picture or to tell a story about the picture (Goldman and Fristoe, 1969). In this way, the subject is not simply naming depicted objects, with single-word responses, nor is he using an oral reading style, but he is probably more inclined to use phrase and sentence forms of connected speech. The examiner selects the pictures and uses leading questions in order to evoke conversational speech and the desired test sounds, and to control the content of the subject's spontaneous speech. Both the use of reading material and situational pictures require a longer period of time to obtain the desired speech sample than does the naming of single-word pictures as in the traditional picture articulation inventory.

A number of studies have been reported which have attempted to determine whether the "spontaneous" and "imitative" methods of assessment result in different articulatory responses. In the former method, a speech sample is elicited from the subject without the examiner saying the desired word; in the latter, the examiner says the word and instructs the subject to repeat it. Winitz (1969) discusses this body of research, but the conclusions are disparate and equivocal. However, it is of interest that many authors have stated that a useful method of predicting the ability of a speaker to correct his misarticulations is to observe the difference in his articulation errors between the spontaneous and imitative approaches, that is, to note which sounds are improved upon stimulation from the examiner (Carter and Buck, 1958).

To communicate with a listener, a speaker must be able to use intelligible speech. If he has defective articulation, his intelligibility may well be reduced. One way, therefore, to measure articulatory skill is to assess how well the listener understands the message: the degree to which the speaker is intelligible. A few investigators have specifically obtained intelligibility measures from cleft-palate speakers. Subtelny et al. (1969) and McWilliams (1954) had their subjects record a series of word lists, and the listeners wrote down what they understood each subject to say. Prins and Bloomer (1965) employed the Rhyme Test procedure (House et al., 1965).

Although articulation and intelligibility are related, they are not identical. In assessing articulation, some index of intelligibility should be included, but the examiner must realize that there is some difference between them. If a speaker is distorting sound elements, although the errors are still "within appropriate phoneme boundaries," he may be perfectly capable of communicating intelligibly. Furthermore, if a speaker is fairly consistent in his sound errors, the listener may be able to decode the message easily, once he learns the speaker's code. If he is randomly inconsistent with his misarticulations, the code is always changing, and thus intelligibility is affected. The particular sounds in error and the number of speech sounds misarticulated will also influence intelligibility. The person who misarticulates many sound elements will undoubtedly be less intelligible than the one who misarticulates only a few. On the other hand, if a speaker misarticulates sounds which occur frequently in the language, he probably would be judged to be less intelligible than one who misarticulates only those of relatively rarer occurrence. Barker (1960, 1962) has devised a system of traditional picture articulation assessment, but in which each sound element is assigned a weighted score based upon the relative frequency of occurrence of American speech sounds.

Some investigators have used the approach of overall judgments of "defectiveness of articulation" (Jordan, 1960; Sherman, Spriestersbach, and Noll, 1959). The usual procedure is to have a group of listeners rate the sample(s) of speech on some type of scale, such as an equal-appearing intervals scale. One end of the scale is designated as normal or mildly defective articulation while the opposite end is designated as severely defective. Each sample is then judged by the listeners as falling somewhere along this continuum. Usually the listeners or judges are not instructed as to a definition of the steps along the scale, other than to give a subjective global rating of defectiveness of articulation, however they wish to use that term. The method of direct magnitude-estimation has also been used in scaling defectiveness of articulation (Prather, 1960). It would seem natural that the listeners' judgments are determined by more features of speech than solely articulation. They are probably reacting to the paralinguistic features of vocal pitch, rate, fluency, voice quality, and so on. Nevertheless, the resultant judgments do tend to correlate rather highly with the number of misarticulations from a phonemic inventory (Jordan, 1960). The point is, however, that the correlations are not unity; that is, judgments of defective articulation are not synonymous with results from traditional articulation tests. The average, unsophisticated listener probably is more inclined to respond to a speaker with a global impression of speech proficiency than he is to make an analytic decision of articulatory skill. Thus, the global ratings of defectiveness may be quite valid if our purpose of assessment is to determine how the speaker sounds. Siegel (1966) states:

> The lay person . . . attends to the speech more in the context of the speaker. . . . The point is that because an individual [the speech pathologist] has become expert in lis-

tening to and classifying patterns of speech, his ears do not necessarily make evaluations that are "true."

RELIABILITY

Winitz (1969) thoroughly reviews the existent literature dealing with the reliability of articulation test results. He suggests that the potential sources of variability can be attributed to the subjects, to the examiner, to the test instrument, and to the interaction of the subject with the examiner. Moll (1968) concludes from his review of published research that articulation and intelligibility measurement techniques are highly reliable measures.

Philips and Bzoch (1969) designed an interesting study concerned with articulation test reliability.

> Ten speech pathologists [each of whom had extensive clinical experience with cleft palate subjects] evaluated tape-recorded articulation responses and connected speech samples of fifty cleft palate subjects. The judges did not train together to reach a predetermined level of agreement. They followed written directions concerning error judgments. Their evaluations were studied to determine levels in intra- and interjudge agreement. The findings indicate satisfactory levels of agreement for judgments of intelligibility of connected speech samples. As determined by percentage of agreement, identification of articulation errors also appears to have satisfactory intra- and interjudge reliability. However, under the conditions of this study, the degree of variability which exists among examiners in identification and classification of articulation errors seriously impairs the reliability of this type of test score. Agreement on classification of error types was below the level of chance. The findings appear to limit the clinical and research interpretations of articulation test scores. These data indicate that only the use of averaged or mean articulation scores would provide a satisfactory degree of reliability. However, the high degree of reliability for intrajudge evaluations indicates that reliability of interjudge agreements on identification and classifications of articulation errors might be improved by redefining and standardizing the criteria for each evaluation. (pp. 33-34)

Thus, Philips and Bzoch's (1969) conclusion seems to contradict Moll's (1968) interpretation. Part of the explanation for the problem of reliability is that there is no standardized test procedure. Also, we are dealing with a subjective perceptual phenomenon. As such, then, each individual unavoidably introduces his own biases and idiosyncrasies into the judgment process.

A WORD OF CAUTION

At the beginning of this paper, I suggested that articulation could be assessed from a physiologic, acoustic, or perceptual orientation. The general theme I have attempted to present is that the primary, critical feature of articulation testing is the effect of the speaker's articulation upon the listener, that is, a perceptual process. With this attitude, then, the physiological and acoustical measures become supplementary to the perceptual. One of the problems with x ray, electromyography, and other techniques in assessing the physiological mechanisms of articulation is that there is more information available than the listener can possibly use. The investigator has difficulty in identifying the physiological correlates of perceptual properties of articulation. The same reaction can be made toward acoustical studies. A problem with the sound spectrograph, for example, is to ascertain what spectral differences make a perceptual difference.

There are several instruments available which give a visible display of the acoustic features of vocal sounds in order for the patient to monitor his vocal output (Borrild, 1968; Risberg, 1968). Though generally these have been developed for the deaf speaker, they have begun to receive rather wide usage with other types of articulatory defective speakers. If the clinician or researcher is not careful, he finds the perceptual criterion becoming supplementary to the acoustic, rather than the other way around. For instance, with one of these devices (the "s-indicator"), the examiner might make such a statement as "The instrument is so good that it displays a defective /s/ which I cannot even hear." Nevertheless, I am not degrading basic research on the physiological and acoustical measures of articulation, since they give us valuable and useful information as to the underlying mechanisms of articulation. Furthermore, this research emphasizes the amount of acoustic and physiologic variation that can occur and still result in adequate speech (for example, Weinberg, 1968). My caution is that if there is an implication of defectiveness or of phonemic structure, then the perceptual property must be the base to which all other data point. The issue somewhat parallels the concern expressed by Moll (1964) relative to the physical or "objective" measures of nasality, which, of course, is also a subjective, perceptual phenomenon. The study by Lubker and Schweiger (1969) is a good example of research on the physiological properties of speech, but in which there is a continual reference to the perceptual significance of the data.

Moll (1968) succinctly discusses the issue of measurement subjectivity:

> . . . all of the measurement procedures . . . involve human listeners, whether it be one examiner scoring articulation test responses or a large group of judges rating connected speech samples. If "subjectivity" is defined as the degree to which human biases and errors of perception might influence measurement, then all of these measures must be considered subjective. This fact, however, has not always been recognized. There often has been a tendency to assume that articulation tests are more objective than judgments of overall articulation ability and that intelligibility measures are more objective than articulation assessments. Since all procedures involve listeners, however, the validity of such assumptions is questionable. (p. 70)

He goes on to state that "At the present time, no satisfactory method of assessing articulation and intelligibility without using human listeners is available" (p. 70).

FUTURE RESEARCH DIRECTIONS

The essential purpose of this paper is to relate the topic of articulatory assessment to features of the dentofacial complex. The determination of such a relationship puts a great deal of responsibility upon the examiner. Not only must he make a valid and reliable assessment of the speaker's articulatory abilities, he must also appraise the speaker's dentofacial morphology and physiology. Then he must conclude whether there is any interaction between the two. If the speaker has an abnormal dentofacial structure and has defective articulation, are they in any way related? Simply because a person has an open bite and misarticulates the sibilants, the examiner must be extremely careful before inferring that the articulatory problem is caused by the condition of the teeth or vice versa. Such studies as that by Weinberg (1968) and Subtelny, Mestre, and Subtelny (1964) are valuable in this regard as guidelines for the clinician.

The relevant issue, however, is whether the method of articulatory assessment is critical in determining any causal relationship between misarticulations and morphology of the dentofacial complex. In other words, does the way in which we test articulation help to resolve the question of "structure determining function"? Obviously, this cannot be answered completely until more research is compiled. The Iowa Pressure Articulation Test (Morris, Spriestersbach, and Darley, 1961) might be considered as an example of this paradigm. The examiner simply judges ("tests") the ability of the speaker to produce the fricatives, plosives, and affricates, that is, those sounds which best discriminate between subjects with adequate from subjects with inadequate velopharyngeal closure. The use of the Templin-Darley Test of Articulation (Templin and Darley, 1960) is merely to prompt the subjects to produce these classes of speech sounds in single-word responses.

Thorough phonetic analyses are required, particularly longitudinal ones, so that the examiner can ascertain changes that might occur as the dentofacial mechanism changes. It would be useful also to consider subjects with abnormal structures who are capable of producing adequate articulatory skills by means of certain compensatory adjustments (Weinberg et al., 1969). In addition, there would be value in performing physiological, acoustical, and perceptual studies of the articulatory assessment of people who are undergoing abrupt modifications of the dentofacial mechanism, such as patients with mandibular resections or tumor removals.

In any situation where one is assessing some aspect of behavior, inevitably the particular bias of the evaluator can influence his judgments. In the case of articulation testing, the examiner may have some preconceived expectations of the speaker's patterns of articulation. The examiner probably anticipates a specific type of speech problem with the child with a cleft palate or the child with an open bite, which therefore might affect the judgments he makes about the articulatory abilities of the speaker. These inclinations may differ between sophisticated and naive listeners. Some research has been done in comparing the results of judgments of articulatory ability with different groups of listeners (for example, Siegel, 1962), but little comparable research has been done with speakers presenting abnormalities of the dentofacial structures. It might be of interest to observe the effect of the examiner's bias with speakers exhibiting certain apparent dentofacial abnormalities. Another interesting approach would be to tape-record speech samples from several different types of articulatory-defective speakers, but to mislabel the diagnosis. For example, instruct the examiner to evaluate the articulation ability of a speaker from a tape recording, but incorrectly inform the examiner that the speaker is a child with cleft palate.

The same general procedure could be done "live," but with the speaker hidden from the examiner's view.

Warren (1968) has reported an interesting series of studies which show that our auditory perceptions change upon repeated presentations of speech material. He simply played recorded tape-loops of normal speakers saying various single words or phrases. During continuous repetitions of the stimuli, listeners simply reported what they heard. Even though the listeners were told that the speech stimuli would not change, they "observed" significant illusory semantic and phonetic changes. In other words, on repeated exposure to speech, our perceptual processes are not static. This effect seems to have considerable relevance to the issue of articulatory assessment. Is the examiner's perceptual judgment the same throughout an articulation inventory? Is the stability the same for skilled and unskilled examiners? These questions are partially answered by research on the inter- and intrajudge reliability of articulation tests, but additional research programs should investigate this matter more carefully.

In the assessment of articulation, we have been concerned almost exclusively with the peripheral processes of articulatory dynamics. One might hope that further research would deal with assessment at "higher, central levels." What are the neurological commands required in normal articulation, and how do these commands differ from those of the speaker with defective speech? Obviously, articulatory movements are skilled motor acts under the control of the central nervous system. In some way, the peripheral structures receive neural instructions programmed to receive their control from "higher" commands. MacNeilage and DeClerk (1969), for example, have explored this area of articulatory motor control. Does the articulatory-defective speaker exhibit an impaired neuromotor command system, or is the impairment one of peripheral execution? Conceivably, our methods of assessment could lead to the solution of this question.

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