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Development of the Speech Perceptuomotor System

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INTRODUCTION

The intent of the present paper is to reflect on the development of the speech perceptuomotor system in light of the infant's evident capacity for intermodal (or, better, amodal) perception, discussed by Meltzoff and by Kuhl at this meeting. The central issue is imitation. How does a child (or, for that matter, an adult) transform a pattern of light or sound into a pattern of muscular controls that serves to reproduce a structure functionally equivalent to the model? The hypothesis to be outlined is that imitation is a specialized mode of action, in which the structure of an amodal percept directly specifies the structure of the action to be performed (cf. Meltzoff and Moore, 1983).

THE GENERAL FUNCTION OF PERCEPTION

Let us begin by considering briefly the function of perception from an ethological perspective (Gibson, 1966, 1979; von Uexküll,1934). The general function of perception is to control action. Perception and action are two terms in a functional system that permits an animal to survive. To survive, an animal must constantly negotiate a physical world, moving around, over or under objects in its path, seeking food or mates, escaping from predators. The actions that an animal takes, its coordinated patterns of goal-seeking movements, are more or less precisely matched to the world it perceives; and the world it perceives is constantly modulated by the actions it takes. Thus, action and perception are mutually entailed components of a single system: each fits the other as key fits lock.

How is the fit achieved? How are the varying patterns of light, sound, temperature, pressure that determine perception transduced into the neuromuscular patterns that determine action? Can we find a single set of descriptive terms that will match all the various sensory modalities with the single modality of action? We may approach an answer to these questions by asking another: What information do light, sound and other modes of energy convey? Following Gibson (1966, 1979) we answer quite generally: Informa-

tion that specifies the structures of objects and events to which action must adapt.

We may note two properties of perceived object-event structures. First, they are amodal. We perceive a desk, say, through a pattern of light structured by its light-reflecting properties, or by touch through the pattern of mechanical resistance it offers to our fingers. A bat, being equipped with sonar, might perceive the desk by virtue of the desk's sound-reflecting properties. Similarly, we normally perceive a spoken word through a pattern of sound, structured by the coordinated articulations of a speaker. To the extent that these articulations reflect radiant energy within the visible spectrum, we may also perceive the word by virtue of its optical structure. The deaf-blind, using the Tadoma method, may even perceive the word by touch (Norton, Schultz, Reed, Braida, Durlach, Rabinowitz and Chomsky, 1977). What we perceive, then, are objects and events, independent, in principle, of the sensory modalities through which we perceive them.

The second point to note about object-event structures is that their perceived qualities vary with the perceiving organism. The "same" object has different utilities for different animals, or for the same animal at different times. Objects and events differ in what von Uexküll(1934) termed their "functional tones", what Gibson (1979) termed their "affordances". The puddle that a person steps over affords a dog an opportunity to drink; the desk that offers support for a writing pad on one occasion may serve as a seat on another; a word spoken in Mandarin is merely a vocalization to someone who knows no Chinese. Thus, different animals perceive different worlds (von Uexküll's Umwelten), each structured by the animal's potential actions, just as its actions are structured by its perceived world.

THE FUNCTION OF SPEECH PERCEPTION

The Speech Percept as Amodal

The first function of speech perception is social and communicative, a pragmatic function analogous to the general function of perception discussed above. As the carrier of language, speech offers meaning, that is to say (very broadly), information conveying the structure of a social world within which an individual may act. The individual, by acting in response, whether linguistically or non-linguistically, then modulates the perceived structure of his social world.

A second function of speech perception, ontogenetically prior to the first and of more immediate interest here, is in language acquisition. While the adult may listen simply for meaning, the learning child must listen both for meaning and for information specifying a talker's articulatory gestures. This second perceptual function therefore controls action in the more limited sense of providing a model for imitation.

Before we consider imitation, let us explicate and justify the claim that speech carries information specifying a talker's articulatory gestures. Notice, first, that this is not the customary account. For example, Abercrombie (1967) characterizes one

form of the information conveyed by speech as linguistic and segmental, intending by this a sequence of phonetic elements, the consonants and vowels of a phonetic transcription. This is certainly correct, at one level of description, as our ability to read and write alphabetically demonstrates. However, a transcription is so far removed from the signal that most people in the world who can speak and understand speech cannot read or write.

What, then, is the difference between the information in a spoken utterance and the information in its written counterpart? Following Carello, Turvey, Kugler and Shaw (1984) (see also Turvey and Kugler, 1984), we may say that the difference is between information that specifies and information that indicates. The information that specifies and information that indicates. The information in a spoken utterance is not arbitrary: its acoustic formation in a spoken utterance is not arbitrary: its acoustic structure is a lawful consequence of the articulatory gestures that shaped it. In other words, its acoustic structure is specific to those gestures, so that a human listener (who knows the language spoken) has no difficulty in following the specifications and organizing his own articulations to reproduce the utterance. By contrast, the form of a written transcription is an arbitrary convention, a string of symbols that indicate to the reader what he is to do, but do not specify how he is to do it. The important point here is that indicational information cannot control action in the absence of information specific to the act to be performed. For example, a road sign indicates that we are to stop, but we can only follow the instruction if we have information specifying our velocity and our distance from the required stopping point (Turvey and Kugler, 1984). Similarly, we can only reproduce an utterance from its transcription, if we have information specifying the correspondences between the symbol string and the motor control structures that must be engaged for speaking. It is these correspondences that the illiterate has not discovered. Just how these two forms of linguistic information are related is, of course, a central issue of speech research. My concern here is merely to make the distinction. For we shall be led astray in our study of speech perception (and so of speech acquisition), if we strive to equate the linguist's description of speech as a string of symbols with the dynamic structure of the speech signal itself.

Consider, here, an early interpretation of the lip-reading studies of McGurk and MacDonald (1976). These authors discovered that listeners' perceptions of a syllable presented over a loudspeaker could be changed, if they simultaneously watched a video-tape of a speaker producing another syllable. For example, presented with audio [ba] and video [da], subjects typically report the latter, optically specified syllable; presented with audio [na] and video [ba], subjects typically report [ma], a combination of the two. Such observations are consistent with the notion that subjects engage two independent phonetic systems, drawing manner and voicing features from the acoustic structure, place of articulation features from the optic structure (MacDonald and McGurk, 1978). This interpretation assumes that we perceive speech by extracting phonetic features and combining them to form phonetic segments—in other words, it assumes that the speech sig-

nal carries information about a string of linguistic symbols. As already remarked, this is true at one level of description. However, this interpretation bypasses the actual event specified by the dynamic acoustic-optic structure and does not address the puzzle of its transformation into a static linguistic symbol.

Moreover, the featural interpretation breaks down in the face of other findings. For example, presented with audio [ga] and video [ba], subjects typically report a cluster [b'ga] or [g'ba]; presented with the reverse arrangement, audio [ba] and video [ga], subjects often report a sort of acoustic-optic blend, [da]. In these instances, the percept corresponds either to both inputs or to neither, so that the notion of two independent and additive phonetic systems break down.

While much remains to be done before we have a satisfactory account of such findings, the effect seems to arise from a process by which two continuous sources of information, acoustic and optic, are actively combined at a precategorical level where each has already lost its distinctive sensory quality (Summerfield, 1979). In other words, the McGurk effect (and, indeed, normal lipreading as practiced in aural rehabilitation) is only possible because acoustic and optic structures specify an amodal event: a coordinated pattern of articulatory action.

Imitation

A general capacity to imitate is rare among animals. The specialized capacity to imitate vocalizations is confined to a few species of birds and of marine mammals, and to man. Here we should distinguish between mimicry and repetition, or reproduction. The Indian mynah bird, for example, mimics human speech quite precisely, within the limits of its vocal apparatus (Klatt and Stefanski, 1974). However, a human speaker repeats the utterances of another (when not deliberately attempting mimicry) by producing a functionally equivalent, but acoustically distinct, pattern of sound. Given within-species individual differences in size and structure, we may reasonably suppose that the production of distinct, yet functionally equivalent, acts is the normal mode of animal imitation, whether in human speech or in, say, the nest-building of a young chimpanzee. In any event, both mimicry and reproduction, call on a specialized capacity for finding in the perceptual array an organized pattern of information specific to an organized pattern of action. To find a pattern the imitator must find both the pieces of an act and their spatio-temporal relations (Fentress, 1984).

Consider, for example, the following transcription of ten attempts by a 15-month old girl to say pen, within a single half-hour's recording session: [mɑˀ,ˇʌ,deˀⁿ,hɪn,ᵐbõ,pʰɪn,tʰⁿtʰⁿtʰⁿ ,ba�^h,dˀauᵛ,buʌ] (Ferguson and Farwell, 1975). Note once again that the transcriptions are merely convenient (and approximate) indicators of what the child did. For what the child evidently did, in each case, was to extract from the sound pattern of pen information specific to certain articulatory gestures, such as lip closure, lingua-alveolar closure, velum lowering, glottal narrowing

and spreading. Thus the child analyzed the word (with varying success) into its components gestures, or pieces, but could not discover, at least motorically, their spatio-temporal relations. Perhaps we have here an instance of the necessary sequence in learning to speak, or indeed in learning to reproduce any act performed by another: first perceptual analysis, then motor synthesis. We can hardly doubt that a capacity to perceive the pieces of an act and their relations, and to reproduce them in our own behavior, rests on some form of structural (anatomical, physiological) correspondence between imitator and model. This observation leads us to a brief digression.

Can non-human animals perceive speech?

The answer to this question must depend on what we mean by "perceive speech." Here we have been misled, it would seem, by the behaviorist view of perception as a mere matter of psychophysical capacity. We have tended to describe speech in purely acoustic terms as a collection of "cues," without regard to the articulatory events that the cues specify, and then to suppose that any animal able to discriminate these cues can perceive speech. Yet the psychophysical capacities of an unlimited set of animals--from the human infant to the chinchilla--may suffice to discriminate among formant transitions, formant onset frequencies, brief silences, patches of noise, and so on. However, these capacities may not suffice to discover the functional relations among the perceptual pieces.

In fact, the perceptual status of communicative signals varies even for closely related species. For example, while two species of macaque (pig-tail and bonnet) and an African vervet may learn an arbitrary discriminative response to contrasting calls of the Japanese macaque, the latter learns the response significantly more rapidly (Zoloth, Petersen, Beecher, Green, Marler, Moody and Stebbins, 1979). Moreover, the processes underlying the Japanese macaque's response to its own calls are evidently localized in the left cerebral hemisphere, while those of the other two species of macaque are not (Petersen, Beecher, Zoloth, Moody and Stebbins, 1978; cf. Heffner and Heffner, 1984). Whether this hemispheric specialization has a perceptuomotor origin (as in the human: see below), we do not yet know. The point here is that, if we show a particular discriminative task to be within the psychophysical competences of two different species, we have not thereby shown their percepts to be equivalent.

In short, if the strucure of perception can properly be said to be tuned to the structure of the perceiver's capacity for action, a non-human animal's perception of speech must differ radically from a human's. What actions of a macaque, say, are controlled by its perception of speech? What events do the acoustic patterns of speech specify for a macaque? Presumably, the patterns do not specify articulatory gestures, and the actions brought under control in the laboratory (such as lever holding or escape from shock) are the arbitrary choices of an experimenter, adventitious and ethologically empty. In other words, the information in speech may indicate to a non-human animal what it should

do in a particular situation, but (pace the mynah bird) the in-
formation cannot specify for the animal, as it does for a human,
the speaker's pattern of articulatory gestures.

PERCEPTUOMOTOR RELATIONS IN THE INFANT

Since the infant, by definition, does not speak, our under-
standing of perceptuomotor development over the first year of life
must be largely inferential. Here I will consider three classes
of evidence, concerning: (1) the adult perceptuomotor system,
particularly its cerebral locus; (2) infant perceptual capacity;
(3) infant behavior, reflecting hemispheric specialization for
speech perception.

The Adult Perceptuomotor System

Aphasia studies for over a century have suggested that the
right cerebral hemisphere of most right-handed individuals is
essentially mute (see, for example, Milner, 1974). Differential
anesthesia of left and right hemispheres by intracarotid sodium
amytal injection (preparatory to possible brain surgery) has con-
firmed this fact experimentally (Milner, Branch and Rasmussen,
1964; Borchgrevink, 1982). Thus, speech motor control is vested
in the left hemisphere of most individuals (roughly 90% of the
population). (The origins of a population diversity, such that
speech motor control is vested in the left hemisphere for some
90%, in the right hemisphere for some 10% of the population are
not yet understood.)

Since any imitative behavior calls for close neurophysiolo-
gical connections between perceptual and motor processes, we might
predict that left hemisphere control of articulation would be
coupled with left hemisphere specialization for speech perception.
Numerous monotic and dichotic studies of normal subjects have con-
firmed this prediction, and have demonstrated a double dissocia-
tion of left and right hemispheres for the perception of speech
and non-speech (e.g. Kimura, 1961a,b; Studdert-Kennedy and
Shankweiler, 1970). Furthermore, studies of split-brain patients
(whose cerebral hemispheres have been surgically separated for
relief of epilepsy) have shown that, while the right hemisphere
may recognize the meaning of a word from its overall auditory
shape, only the left hemisphere can carry out the phonetic analy-
sis necessary to establish a new word in an individual's lexicon
(Zaidel, 1976, 1978). (Phonetic analysis refers, of course, to
analysis of a word into its articulatory components and to recog-
nition of the relations among them, as discussed above.) Thus,
we have solid evidence that the adult speech perceptuomotor sys-
tem is a left hemisphere function.

Infant Perceptual Capacity

As is well known, infants in the first six months of life
can discriminate virtually any adult speech contrast on which
they are tested (for reviews, see Aslin, Pisoni and Jusczyk, 1983;
Eimas, 1982). Much of the infant research has been carried out
with synthetic speech continua on which adults typically display

"categorical perception," that is, good discrimination between
sounds that fall into different adult phonetic categories, but
poor discrimination between sounds that fall into the same phone-
tic category. Infants have generally displayed a similar pat-
tern, and this outcome has been interpreted as evidence that in-
fants are prepared at birth, or very soon after, to perceive
speech in terms of adult phonetic categories (Eimas, 1982).

This interpretation has been weakened by two sets of find-
ings. First, we now know that categorical perception is not pe-
culiar to speech, nor even to audition (e.g. Pastore, et al.,
1977). Second, Kuhl and her colleagues (Kuhl, 1978; Kuhl and
Miller, 1978; Kuhl and Padden, 1983) have demonstrated categori-
cal discrimination along synthetic speech continua for macaques
and chinchillas. The issue is complicated by the fact that
speakers of different language.. m... display different boundaries
between the phonetic categories of a continuum (see Repp, 1984),
and we may suspect (following the argument of the previous sec-
tion) that quite different processes underlie the seemingly
equivalent human and animal behavior. However, let us assume
that categorical perception is essentially a psychophysical phe-
nomenon, susceptible perhaps to effects of learning and atten-
tion, but based on the psychoacoustic tuning of the mammalian
auditory system.

Nonetheless, we have ample other evidence that speech al-
ready has a unique status for the infant within a few hours or
days of birth. For example, neonates can discriminate speech
from non-speech (Alegria and Noirot, 1978, 1982), prefer speech
to non-speech (Hutt, Hutt, Lenard, Bernuth and Muntjewerff, 1968),
and prefer their mother's voice to a stranger's (DeCasper and
Fifer, 1981), provided she speaks with normal intonation rather
than in word-by-word citation (Mehler, Barrière and Jasik-
Gerschenfeld, 1978). However, the strongest evidence for the
unique status of speech comes from studies of infant hemispheric
specialization.

Cerebral Asymmetry for Speech in Infants

A number of studies has demonstrated dissociation of the
left and right sides of the brain for perceiving speech and non-
speech sounds at, or very shortly after, birth. These include
both physiological and behavioral studies. For example, Molfese,
Freeman and Palermo (1975) measured auditory evoked responses,
over left and right temporal lobes, of 10 infants aged from one
week to 10 months. Their stimuli were four naturally spoken
monosyllables, a C-Major piano chord and a 250-4000 Hz burst
of noise. Median amplitude of response was higher over the left
hemisphere for all four syllables in nine out of ten infants,
higher over the right hemisphere for the chord and the noise in
all ten infants. Molfese (1977) has reported similar asymmetries
for syllables and pure tones in neonates.

Dissociation between responses to speech and non-speech has
also been demonstrated by Best, Hoffman and Glanville (1982).
These authors tested forty-eight 2- 3- and 4-month old infants

for ear differences in a memory-based dichotic task. They used
a cardiac orienting response to measure recovery from habitua-
tion to synthetic stop-vowel syllables and to Minimoog simula-
tions of concert A (440 Hz), played on different instruments.
In the speech task, a single dichotic habituation pair (either
/ba-da/ or /pa-ta/) was presented nine times at randomly varying
intervals. On the 10th presentation, one ear again received its
habituation syllable, while the other received a test syllable
(either /ga/ or /ka/), differing in place of articulation from
both habituation syllables. An analogous procedure was followed
in the musical note task. The results showed significantly
greater recovery of cardiac response for right ear test syllables
in the 3- and 4-month olds, and for left ear musical notes in all
age groups. The authors proposed that right-hemisphere memory
for musical sounds develops before left-hemisphere memory for
speech sounds, and that the latter begins to develop between the
second and third months of life.

A further, particularly telling result, in light of the pre-
sumed amodal nature of the speech percept, comes from a study by
MacKain, Studdert-Kennedy, Spieker and Stern (1983). These au-
thors showed that 5- to 6-month old infants preferred to look at
the face of a woman repeating the disyllable they were hearing
(e.g. [zuzi] than at the synchronized face of the same woman
repeating another disyllable (e.g. [vava]). Thus, as in the
study of Kuhl and Meltzoff (1982; Kuhl, this meeting), infant
preferences were for natural structural correspondences between
acoustic and optic information, specifying the same articulatory
event.

However, the most remarkable aspect of the study by MacKain,
Studdert-Kennedy, Spieker and Stern (1983), was that infant pref-
erences for a match between the facial movements they were watch-
ing and the speech sounds they were hearing was only significant
when the infants were looking to their right sides. We can in-
terpret this result in the light of work by Kinsbourne and his
colleagues (e.g., Kinsbourne, 1972; Lempert and Kinsbourne, 1982).
Their work suggests that attention to one side of the body may
facilitate processes for which the contralateral hemisphere is
specialized. If this is so, we may infer that infants with a
preference for matches on their right side were revealing a left
hemisphere sensitivity to articulation specified by acoustic and
optic information.

The work by MacKain and her colleagues has not yet been
replicated. But if it proves reliable, we have some evidence
that 5- to 6-month old infants, close to the onset of babbling,
already display a left hemisphere sensitivity to the amodal struc-
ture of speech events. For the moment, this seems to be close as
we can come to detecting an incipient capacity for imitation on
which spoken language is based.

SUMMARY AND CONCLUSIONS

Perception and action are mutually entailed components of a
single system. Their interlocking operation is possible because

the information picked up by a perceptual system is amodal and
directly specifies, within the constraints of the actor's goal,
the action to be performed.

Imitation is a specialized mode of action, requiring the
imitator to find in the act of a model both the pieces of the
act and their spatio-temporal relations. Imitation also calls
for close neurophysiological connections between perception and
motor control. For speech these perceptuomotor connections are
localized in the left cerebral hemisphere.

Studies of infant speech perception have shown that infants
are sensitive to structural correspondences between acoustic and
optic specifications of speech, and that their left cerebral
hemispheres are differentially activated by speech sounds soon
after birth. We also have preliminary evidence for left hemi-
sphere sensitivity to the amodal structure of speech by the 5th
or 6th month of life. This sensitivity may be a precursor of
the infant's capacity to imitate.

The approach to speech perceptuomotor development outlined
above also promises an ontogenetic solution to the vexed problem
of the incommensurability of the speech acoustic signal and its
linguistic description. The approach distinguishes between the
dynamic information conveyed by an act and the static information
in a symbol string. Thus, linguistic units are not postulated
as part of the infant's native endowment. Rather they are seen
as elements that emerge from a self-organizing system of percep-
tuomotor control (cf. Lindblom, MacNeilage and Studdert-Kennedy,
1983).

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