

# TOWARD A MODEL OF PHONEME PERCEPTION

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Hemisphere asymmetry in phoneme perception was analyzed. Three basic mechanisms underlying phoneme perception are proposed. Left temporal lobe would be specialized in: (1) ultrashort auditory (echoic) memory; (2) higher resolution power for some language frequencies; and (3) recognition of rapidly changing and time-dependent auditory signals. An attempt was made to apply some neurophysiological mechanisms described for the visual system to phoneme recognition in the auditory system.

*Keywords: Phoneme perception, model of language, sensory memory, brain asymmetry.*

“Language comprehension is an everyday phenomenon which we all accept, yet nobody knows what it means in terms of brain activity” (Seldon, 1985, p. 273). During the last decades evident advances in linguistics, neurophysiology, and aphasiology have been achieved. Nevertheless, language processing in the brain is still unclear and poorly understood. How does the brain process an acoustic signal to recognize phonemes? How is it possible to perceive an integrated and unitary phoneme?, And, which are the specific mechanisms underlying hemisphere asymmetry in language perception? These represent just some of the many questions that have arisen. Great interest has been devoted to the analysis of neurophysiological mechanisms underlying perception and pattern recognition in the visual system since the first publications of Lettvin, Maturana, McCulloch and Pitts (Lettvin et al., 1959), and Hubel and Wiesel’s research work on visual processing in the brain (Hubel & Wiesel, 1961, 1962, 1963, 1965). Some basic similarities should exist between pattern recognition in the visual system and language perception in the auditory system.

Some departing points may be considered:

- (1) Neural organization for different sensory systems is similar (Konorski, 1967). Consequently, the same principles applied to pattern recognition in the visual system are to be found in the auditory system with regard to language perception. Nevertheless, the auditory system presents some additional characteristics not shared by the visual system;
- (2) auditory information is sequential and time-depending, not simultaneous. Some additional time-processing mechanisms are expected to be found; and,
- (3) language recognition is asymmetrical. Language is lateralized to the left hemisphere in most people. Consequently, some specific operations that the left hemisphere is performing, but not, or at least, not to the same extent, the right hemisphere in most individuals, are expected to be found.

The above points pose the questions: What is indeed cerebral asymmetry with regard to language perception? And which are those specialized activities the left, but not the right hemisphere, is performing?

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Language recognition implies at least:

- (1) detection of some critical features in the acoustic signal for perceiving phonemes (phoneme recognition);
- (2) recognition of phoneme sequences for perceiving morpholexical units (word identification), and
- (3) cross-modality associations (i.e., a phoneme sequence is associated with a visual and/or other modality percept) to understand meaning.

There are in consequence, different levels of language recognition, at least: phonemic, lexical, and semantic. In case of brain damage, any one of these three levels (phonemic, lexical, and semantic) can be independently impaired (in pure word-deafness, in Wernicke's aphasia, and in semantic anomia) (Alexander & Benson, 1991; Benson, 1979, 1988a, 1988b; Kertesz, 1985; Luria, 1966, 1976) pointing to the fact that they represent activities carried out by different cortical areas of the left cerebral hemisphere. Figure 1 presents a diagram of the critical operations that the left temporal cortex might supposedly be performing in language recognition.

The acoustic signal arrives to the ear (A), and in the inner ear a first frequency analysis is performed (B): at the basilar membrane, different segments respond to different frequencies. There is in consequence, a first topic frequency discrimination. At the primary auditory cortex there are neurons (C) highly tuned-to-specific-frequencies which respond to intensity changes within some particular frequency bands (Brugge & Reale, 1985; Merzenich & Brugge, 1973). The primary cortex contains a tonotopic map in which the relative position of a frequency projection is proportional to the logarithm of the frequency (Romani et al., 1982). The existence of certain proprieties in the acoustic signal, for example, some frequency changes from *fo* to *fk* in a given *t* time (transition), functional in a specific phonological system (D) allows a feature recognition (E). The simultaneous existence of some features in the signal (F) coinciding with a particular phonemic category in the listener's language (G) implies the recognition of a phoneme (H). There is a *first categorical judgment* about the belonging to one of a relatively small number (about 14–40) of sound units (phonemes) in the language. Presumably, this type of analysis is accomplished in the first temporal gyrus around the primary auditory cortex.

Phoneme chains are integrated into more complex units (morpholexical units) (K). Morpholexical units are organized in a verbal-acoustic memory (memory for words) (J), formed with the repeated presence of identical phonemic sequences (I). There is a *second categorical judgment*. Supposedly, the first and second temporal gyri could be involved in this second level of recognition. Verbal-auditory memory defects are observed in cases of Wernicke's aphasia (Luria's acoustic-amnesic aphasia). In such cases, impairments in the lexical repertoire are evident.

An acoustic-verbal percept, corresponding to a morpholexical language unit (word) is associated with some images belonging to other perceptual systems (visual, tactile, etc.) leading to the recognition of the meaning of that morpholexical unit (N). At this point, there is a *third categorical judgment*. Long-term (M) and short-term (N) memory systems would be also involved. Temporo-occipital and parieto-occipital left brain areas most likely are critical in this cross-modality associative learning and language meaning understanding.

There are at least two indirect proofs of the existence of feature detectors in the auditory system:

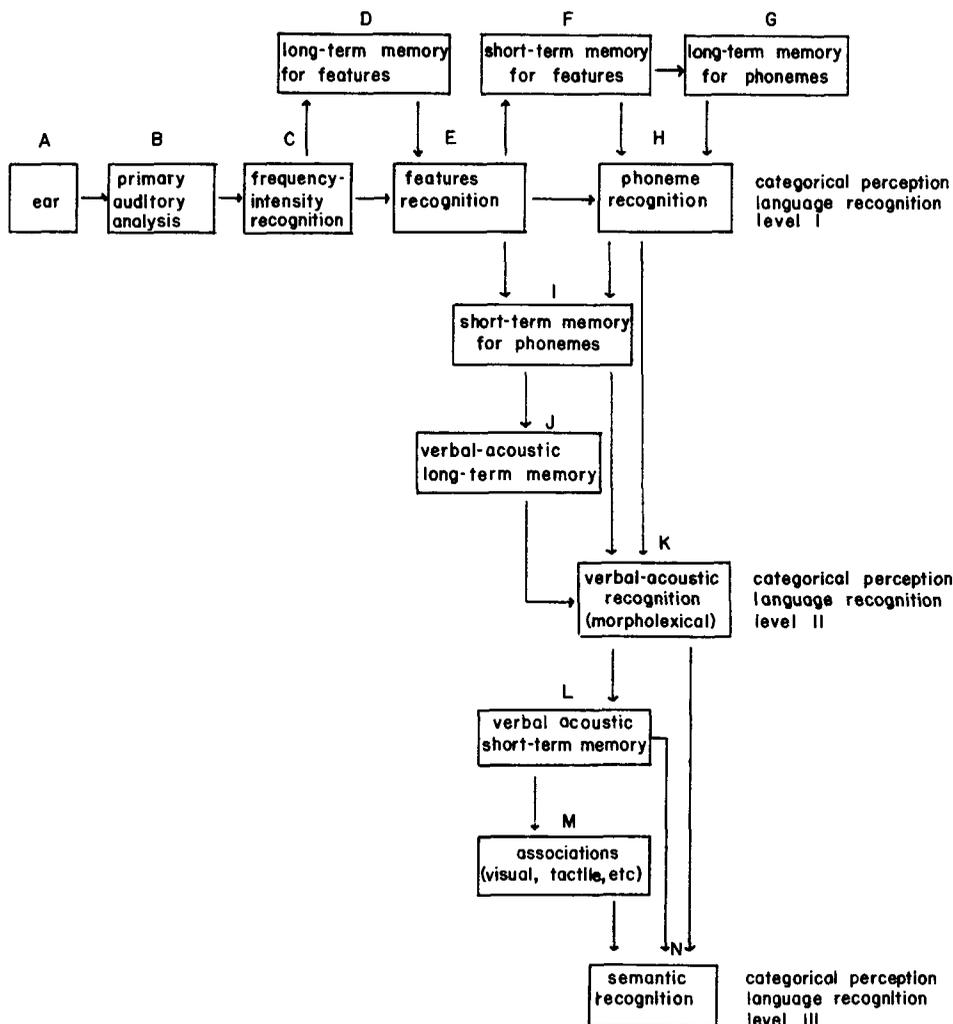


FIGURE 1 A proposed diagram model for language recognition.

- (1) It has been shown that babies can have phonemic perception. They can distinguish consonantic and vocalic contrasts, and they can discriminate verbal and nonverbal stimuli (Eimas et al., 1971; Eimas, 1974; Kasman, 1977). This supposes the existence of highly specialized neuronal populations functioning since very early in life, and
- (2) in phoneme discrimination tasks, the continuous presentation of the same auditory stimulus (phoneme) produces a displacement of the phonemic boundary in the direction of the adaptation stimulus (Eimas & Corbit, 1973; Cole, 1977). That is, there is a selective adaptation to certain phoneme features with their continuous presentation. A sort of detector for acoustic features may be in consequence supposed.

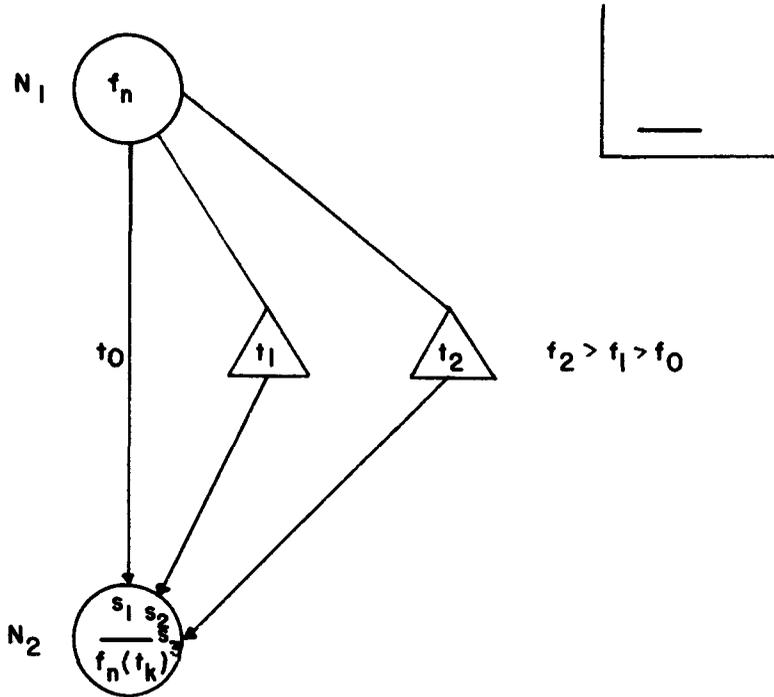


FIGURE 2 Detection of the stable phase of a formant, based in different synaptic delays. Only when  $f_n$  is activated during a time  $t_k$ , a response at  $N_2$  level appears.  $S$  refers to the synaptic coefficient.

## PARAMETERS OF HEMISPHERE ASYMMETRY

Hemisphere asymmetry does not refer just to language perception per se, nor even to phoneme recognition. Rather, hemisphere asymmetry refers to some specific types of phonemic perception. In consequence, there must be some specialized underlying neuronal operations supporting left hemisphere asymmetry in those specific types of phoneme recognition.

How does left hemisphere auditory processing differs from right hemisphere auditory processing?, represents a fundamental question to understand brain organization of language perception.

### *Long-Term and Short-Term Memory Mechanisms*

Two different types of memory can be involved in phoneme perception: (1) a long-term auditory verbal memory, and (2) a short-term auditory verbal memory.

Long-term auditory verbal memory is represented by those life-lasting learnings to perform some functional phoneme discriminations, functional in a specific phonological system. Some phonemes appear roughly throughout all the world languages (e.g., /p/ and /m/); others, are specific for some particular languages or language groups (e.g., the Spanish /r/) (Jakobson, 1956). The existence of an *integrative neuron* (a neuron or neuronal population with several inputs and one single output) might be proposed. The output is a function of the input proprieties:  $O = f(I)$ . Fur-

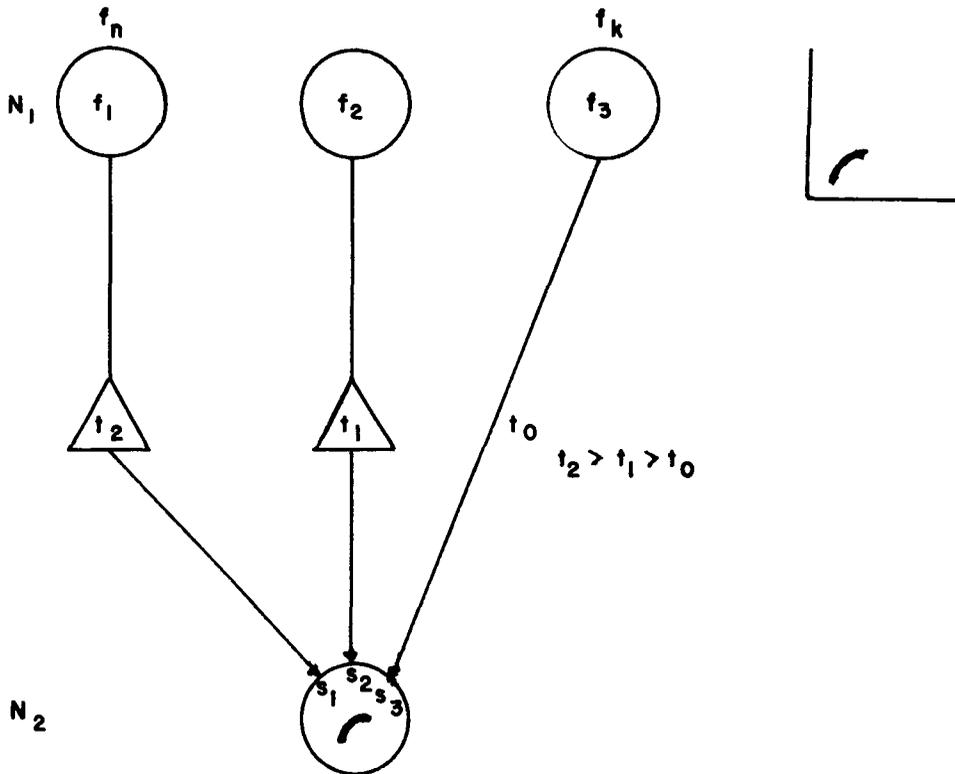


FIGURE 3 Detection of a formant transition, based in different synaptic delays. Only when the units  $f_1, f_2, f_3$  are activated in sequence, a response at  $N_2$  level is obtained.

ther, it could be assumed that, with every repeated synaptic stimulation, a change in the neuron threshold appears (i.e., there is some facilitation with identical repeated stimulation). There will be a *synaptic coefficient* ( $S$ ) that changes with every activation of that synapsis. The threshold would decrease with repeated activation, and, in consequence, a lower magnitude of the inputs to obtain the same single output is required. The synaptic coefficient would then be inversely related with the threshold. In other words, there is a long-term learning resulting from repeated stimulation of the same neuron assembly (Hebb, 1949), corresponding to the neural processing of a particular phoneme. Of course, for morpholexical and semantic language recognition some long-term memory systems would also exist.

Short-term memory is involved at different levels in phoneme recognition. First, an ultrashort (echoic) feature memory is required for phoneme recognition (first categorical judgment). Second, a phoneme short-term memory is necessary for word recognition (second categorical judgment), and third, a word short-term memory is required for semantic understanding (third categorical judgment). Studdert-Kennedy (1976) has pointed out that we require an ultrashort-term auditory memory (about 100 ms) for phoneme recognition.

Two observations should be mentioned:

First, Ardila, Montañes and Gempeler (1986) observed that temporally segmented words were better recognized when presented to the right ear, while the left ear

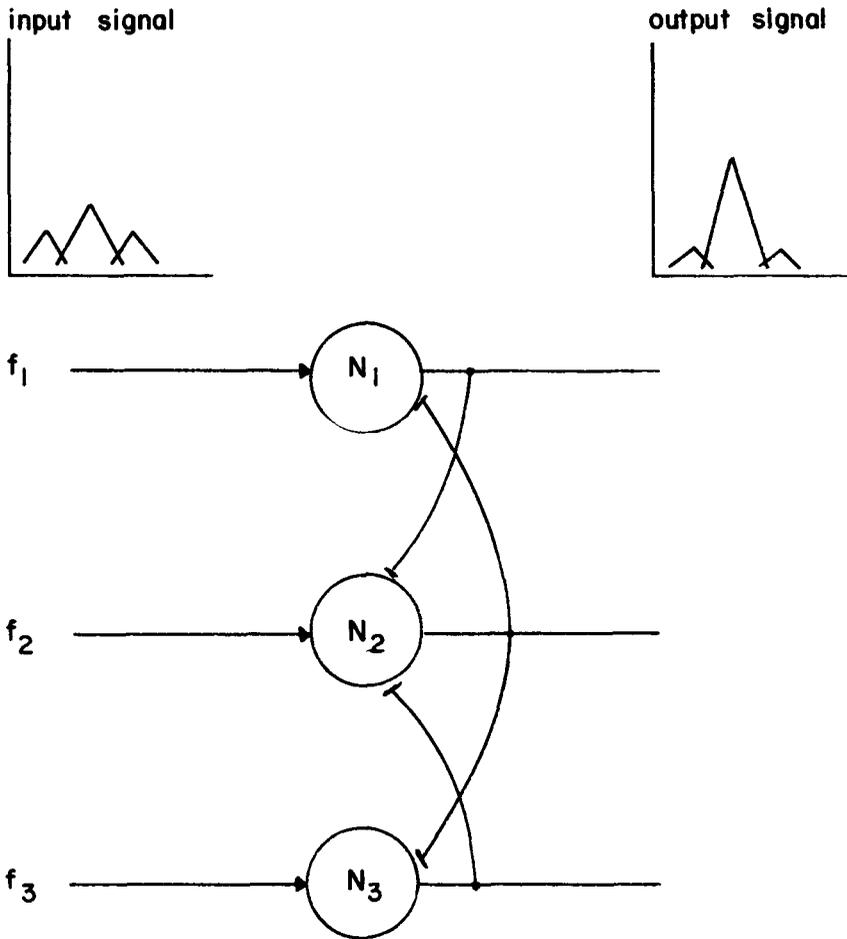


FIGURE 4 Lateral inhibition mechanism for increasing contrasts.

simultaneously received a continuous interfering white noise, than in the inverse situation (i.e., segmented words were presented to the left ear, interfering white noise was presented to the right ear). That means echoic verbal memory has an asymmetrical hemispheric organization. And there is a better maintenance of the verbal acoustic information (during some milliseconds) when word segments are presented to the right than to the left ear (while the contralateral ear is receiving an interfering signal). Echoic memory duration has been estimated in about 200–250 ms (Ardila, Montañes & Gempeler, 1986; Massaro, 1975).

Second, in cases of right temporal damage an impairment in echoic memory (using the same paradigm of segmented speech while presenting a contralateral auditory interfering white noise) when the information is presented to the left (but *not* the right) ear has been observed. In cases of left temporal damage, echoic memory is impaired when the information is presented to *either* ear (Ardila, Montañes, & Gempeler, 1982). It means verbal echoic memory is asymmetrical and it most likely represents one of the underlying parameters for asymmetry in phoneme recognition and language comprehension.

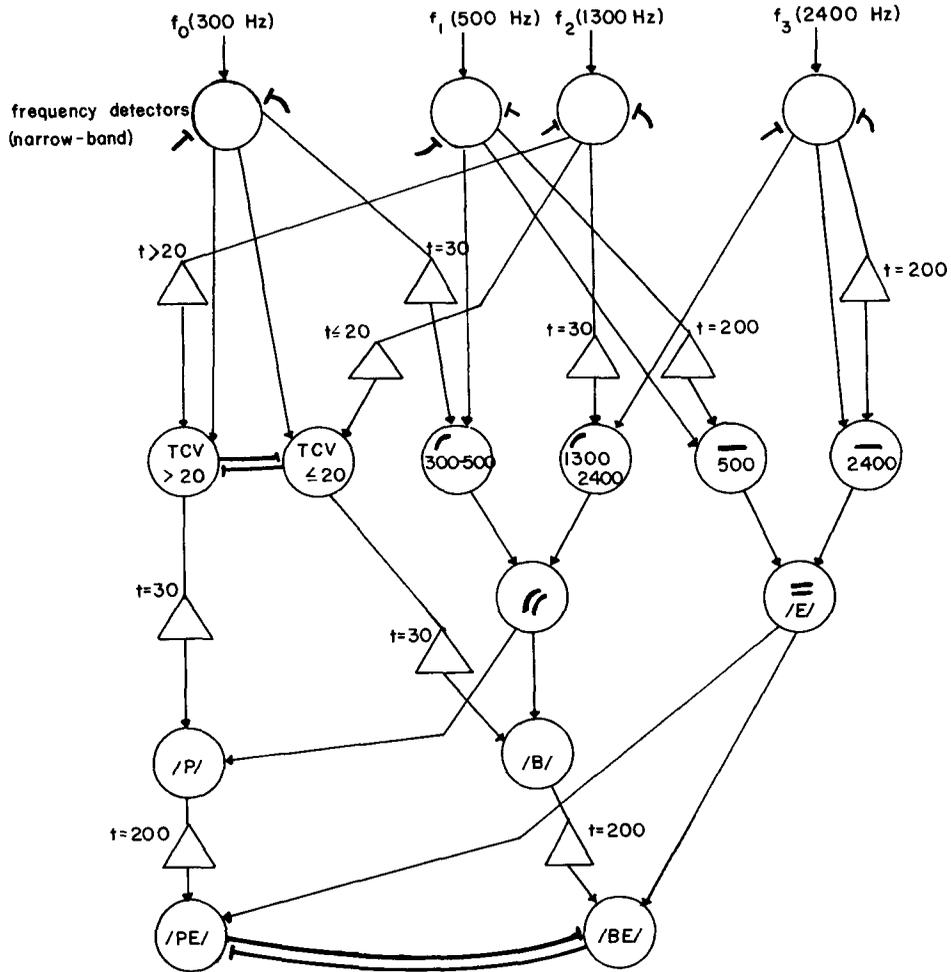


FIGURE 5 Phonemic and syllabic perception. There exists a process of detection of progressively more complex features of the acoustic information.

*Spectral Resolution Power*

It has been established that asymmetry for phoneme recognition only refers to some phoneme categories, and not to every language phoneme (e.g., Darwin, 1975). Asymmetry in phoneme recognition has been observed with stop phonemes, but neither with fricative phonemes nor vowels.

Stop phonemes (asymmetrically recognized) are different from fricative phonemes (nonasymmetrically recognized) at least in the following parameters: (1) they include narrow-band formants; (2) they include rapidly changing signals (e.g., voice onset time, formant transitions); and (3) they are based on a lower frequency spectrum (from about 300 up to about 3000 Hz) than fricative phonemes frequency spectrum (from about 2000 Hz up to about 10,000 Hz). Hence, the left hemisphere should contain some neurophysiological mechanisms capable of processing these information parameters critical in stop phonemes recognition (to distinguish narrow-band

formants, that is, to discriminate changes in intensity accurately, i.e., intensity borders; to detect rapidly changing signals; and to have an adequate auditory spectral resolution for those frequencies existing in stop phonemes).

Ardila (1983, 1984, 1985) developed Stevens-type (Stevens, 1974; Stevens & Volkman, 1940) psychophysical measurement scales for pitch. The experimental paradigm used was the following: with the subject using headphones, two independent psychophysical scales were constructed (for the right and for the left ear), while the contralateral ear was simultaneously receiving an interfering white noise. At least for the stop phonemes language frequencies (up to 3000 Hz) different psychophysical relations were found, with a better frequency resolution power for the right ear psychophysical measurement scale. This observation points to a better left hemispheric frequency resolution power for the stop phonemes frequencies.

### *Time-Dependent Signal Recognition*

Efron (1963) suggested that the ability to perform fine temporal discriminations between sensory inputs is lateralized to the left hemisphere. Phonemic perception is based in the ability to perform fine temporal discriminations. It has been observed that patients with left temporal damage present a decrease in temporal resolution when using stimuli presented contralaterally to the side of the lesion (Lackner & Teuber, 1973) and impairments in temporal summation are observed (Baru, 1971). Voiced/voiceless errors (due to an impairment to recognize the voice onset time) on the other hand, are maximum in Wernicke aphasia with regard to other aphasia groups (Ardila et al., 1989), and perception of temporal order and event duration are disrupted in cases of left-hemisphere damage (Needham, & Black, 1970; Swisher & Hirsh, 1972).

Phoneme identification supposes the discrimination of several phonetic features: (a) voicing, (b) place of articulation, and (c) manner of articulation. Temporal lobe aphasia patients present more consonant than vowel errors; and substitutions involving a single phonetic feature (voicing, place of articulation, or manner of articulation) are most common (Ardila et al., 1989; Blumstein, 1981). This might be related to a stronger lateralization for those acoustic cues embedded in consonants. Using dichotic listening technique, a right-ear advantage for consonants, but not for vowels, has been demonstrated (Blumstein, 1977). By the same token, no hemispheric differences in the auditory evoked responses after stimulation with vocalic sounds are found (Molfese & Erwin, 1983). It must be underlined that vocalic phonemes contain steady, not temporally changing, formants. Consonantic phonemes, particularly stop phonemes, on the other hand, contain rapidly changing formants.

As mentioned above, brain asymmetry is observed not in all consonants but only in certain consonantic groups: It is maximal for stops, minimal for liquids, and non-existing for fricative phonemes (Darwin, 1975; Dwyer, Blumstein & Ryalls, 1982; Cutting, 1974). This means that hemispheric lateralization exists only for those rapidly-changing auditory signals contained in stop but not in fricative phonemes. This conclusion is supported by experiments on acute timing perception which have consistently produced a right ear (left hemisphere) advantage (Mills & Rollman, 1979; Schwartz & Tallal, 1980). It is noteworthy that left hemisphere specialization for time-dependent signal recognition is not restricted to auditory signals, but is also observed in other sensory systems (Hammond, 1981). This ability to discriminate time-dependent signals could represent a basic parameter of left hemisphere specialization and brain asymmetry.

In summary, asymmetry in phoneme recognition refers at least to: (1) some differences in ultrashort maintenance of the acoustic signal (echoic verbal memory); (2) a higher spectral resolution power able to detect frequency sonority borders in some phoneme groups; and (3) a timing mechanism responsible for the detection of time-dependent rapidly changing signals.

The next question that obviously arises is, which are the neurophysiological mechanisms supporting these brain differences.

## NEUROPHYSIOLOGICAL MECHANISMS

It can be supposed that the underlying neurophysiological mechanisms responsible for language perception in the auditory system, are the same neurophysiological mechanisms proposed for other sensory systems, particularly, for the visual system (Konorski, 1967). The question that arises is, how are they working in the auditory system? Auditory information represents sequential time-dependent information. Necessarily, some additional mechanisms should be expected for processing time-dependent signals.

It could be supposed that in the auditory system between neuron A situated at a first level and neuron B situated at a second level, multiple connections may exist. It could be further supposed that there are different transmission speeds in the various existing connections between neuron A and neuron B (due to the length, diameter or properties of the pathways). In other words, it could be supposed that there are alternative pathways with different synaptic delays (D) (see Figure 2). Such synaptic delays allow an ultrashort-term maintenance of the information for some milliseconds, and its delayed use, when a further event occurs (i.e., an ultrashort auditory memory).

This mechanism can be useful for detecting a stable frequency bands (as is the case with vowels), and for detecting transitions (as it is the case with stop phonemes). In this latter case, information proceeds from different neurons tuned to distinct frequencies (frequency detectors in the primary auditory cortex) (see Figure 3). It is known that for perceiving a formant transition it is not required to scan all the frequencies; short-lasting stable frequencies situated at intermediate frequency points, and sequentially presented, are perceived as a phoneme transition (Ardila, 1983; Warren, 1976) (i.e., time-dependent signal recognition).

In the visual system the importance of the lateral inhibition mechanism is well recognized. It was initially proposed by Hartline and Ratliff (1957) as the basic neurophysiological mechanism for discriminating changes in intensity (luminosity borders). Lateral inhibition can be useful in increasing the contrast between two adjacent areas with different luminosity (border detectors). It can be supposed that the same lateral inhibition mechanism might exist in the auditory system for getting a better frequency discrimination (intensity change zones, i.e., narrow-band formant border discrimination), as illustrated in Figure 4. This mechanism would be helpful in separating close situated intensity changes in the auditory signal; that is, discriminating formant borders by increasing contrasts (i.e., higher resolution power to detect frequency sonority borders), particularly with narrow-band formants (e.g., in stop phonemes).

To recognize the phoneme /b/, the syllable /be/, and to oppose the syllable /be/ to the syllable /pe/ supposes at least:

1. A fundamental frequency ( $f_0$ ) with a maximum voice onset time (VOT) of about 20 ms.
2. A transition from about 300 Hz ( $f_0$ ) to 500 Hz (first formant); and simultaneously, a transition from 1300 Hz (locus for the second formant for /b/) to 2400 Hz in a  $t$  time (transition time) lasting about 20–50 ms.
3. A stable phase (about 200 ms) corresponding to the vowel /e/ with at least two formants, the first situated around 500 Hz and the second in 2400 Hz.

Figure 5 illustrates in a simple way the processing that might be carried out.

## CONCLUSIONS

Current literature allows to suppose that left hemisphere specialization for phoneme perception refers only to some parameters contained in a few phoneme categories. Hemispheric asymmetry in processing verbal auditory information could include: differences in echoic memory, differences in resolution power for some language frequencies, and differences in the recognition of time-dependent information.

Some neurophysiological mechanisms proposed for visual perception are potentially useful to understand how the brain might be processing language information. However, additionally, auditory information represents a type of sequential and time-dependent information. Some mechanisms responsible to process timing are expected to be found in phoneme perception in the auditory system.

## REFERENCES

- Alexander, M. P., & Benson, D. F. (1991). The aphasias and related disturbances. In R. J. Joynt (Ed.) *Clinical neurology*, Philadelphia: Lippincott.
- Ardila, A. (1983). Hacia un modelo de la percepcion del lenguaje [Toward a model of language perception]. In A. Ardila (Ed.), *Psicobiologia del lenguaje*. Mexico: Trillas.
- Ardila, A. (1984). *Neurolinguistica: Mecanismos cerebrales de la actividad verbal* [Neurolinguistics: brain mechanisms of verbal activity]. Mexico: Trillas.
- Ardila, A. (1985). Pitch perception and cerebral asymmetry. *XXII International Congress of Psychology*. Leipzig
- Ardila, A., Montañes, P., & Gempeler, J. (1982). Memoria ecoica y reconocimiento del lenguaje: alteraciones en lesiones del lobulo temporal [Echoic memory and language recognition: impairments with temporal lobe damage]. *Neurologia en Colombia*, 6, 176–176.
- Ardila, A., Montañes, P., & Gempeler, J. (1986). Echoic memory and language perception. *Brain and Language*, 29, 134–140.
- Ardila, A., Montañes, P., Caro, C., Delgado, R., & Buckingham, H. W. (1989). Phonological transformations in Spanish-speaking aphasics. *Journal of Psycholinguistic Research*, 18, 163–180.
- Baru, V. (1971). Absolute threshold and frequency difference limens as a function of sound duration. In G. V. Gersuni & J. Rose (Eds.) *Sensory processes at the neural and behavioral levels*. New York: Academic Press.
- Benson, D. F. (1979). *Aphasia, Alexia, and Agraphia*. New York: Churchill Livingstone.
- Benson, D. F. (1988a). Classical syndromes in aphasia. In F. Boller, J. Grafman, G. Rizolatti, and H. Goodglass (Eds.) *Handbook of Neuropsychology*, vol. 1. Amsterdam: Elsevier.
- Benson, D. F. (1988b). Anomia in aphasia. *Aphasiology*, 2, 229–236.
- Blumstein, S. E. (1981). Phonological aspects of aphasia. In M. T. Sarno (Ed.), *Acquired aphasia*. New York: Academic Press.
- Blumstein, S. E., Tartir, V. C., Michel, D., Hirsch, B., & Letter, E. (1977). The role of the distinctive features in the dichotic perception of vowels. *Brain and Language*, 4, 508–520.
- Brugge, J. F., & Reale, R. A. (1985). Auditory cortex. In A. Peters, & E. G. Jones (Eds.) *Cerebral Cortex, vol 4: Association and auditory cortices*. New York: Plenum Press.

- Cole, R. A. (1977). Invariant features and feature detectors: some developmental implication. In S. J. Segalowitz & Gruber, F. A. (Eds.) *Language development and neurological theory*. New York: Academic Press.
- Cutting, J. E. (1974). Two left hemisphere mechanisms in speech perception. *Perception and Psychophysics*, 16, 601–612.
- Darwin, C. J. (1975). Ear differences and hemisphere specialization. In B. Milner (Ed.) *Hemispheric specialization and interactions*. Cambridge, MA: The MIT Press.
- Dwyer, J., Blumstein, S. E., Ryalls, J. (1982). The role of duration and rapid temporal processing on the lateral perception of consonants and vowels. *Brain and Language*, 17, 272–286.
- Efron, R. (1963). Temporal perception, aphasia and deja-vu. *Brain*, 86, 403–424.
- Eimas, P. D. (1974). Auditory and linguistic processing of cues for place of articulation by infants. *Perception and Psychophysics*, 16, 513–523.
- Eimas, P. D., & Corbit, J. D. (1973). Selective adaptation of linguistic features detectors. *Cognitive Psychology*, 4, 99–109.
- Eimas, P. D., Siqueland, E. R., Jusczyk, P., & Vigorito, J. (1971). Speech perception in infants. *Science*, 171, 303–306.
- Hammond, G. R. (1981). Finer temporal acuity for stimuli applied to the preferred hand. *Neuropsychologia*, 19, 325–330.
- Hartline, H. K., & Ratliff, F. (1957). Inhibitory interaction of receptor units in the eye of limulus. *Journal of General Physiology*, 40, 357–376.
- Hebb, D. (1949). *The organization of behavior*. New York: Wiley.
- Hubel, D. H. & Wiesel, T. N. (1961). Receptive field of single neurons in the cat's striate cortex. *Journal of Physiology*, 148, 574–591.
- Hubel, D. H. & Wiesel, T. N. (1962). Receptive fields, binocular interactions and functional architecture in the cat's visual center. *Journal of Physiology*, 160, 106–154.
- Hubel, D. H. & Wiesel, T. N. (1963). Receptive field of cells in striate cortex of very young, visually inexperienced kitten. *Journal of Neurophysiology*, 26, 994–1002.
- Hubel, D. H. & Wiesel, T. N. (1965). Receptive fields and functional architecture in two nonstriate visual areas (18 and 19) of the cat. *Journal of Neurophysiology*, 28, 229–289.
- Jakobson, R. (1956). Two aspects of aphasia and two types of aphasic disturbances. In R. Jakobson, & M. Halle (Eds.) *Fundamentals of Language*. The Hague: Mouton.
- Kasman, A. E. (1977). Hemispheric asymmetry in processing dichotically presented speech and non-speech stimuli by infants. In S. J. Segalowitz, & F. A. Gruber (Eds) *Language development and neurological theory*. New York: Academic Press.
- Kertesz, A. (1985). Aphasia. In J. A. M. Frederiks (Ed.) *Handbook of clinical neurology*, vol 45: *Clinical neuropsychology*. Amsterdam: Elsevier.
- Konorski, J. (1967). *The integrative activity of the brain*. Chicago: The University of Chicago Press.
- Lackner, J. R., & Teuber, H. L. (1973). Alterations in auditory fusion thresholds after brain injury in man. *Neuropsychologia*, 11, 409–415.
- Lettvin, J. Y., Maturana, H. R., McCulloch, W. S., & Pitts, W. H. (1959). What the frog's eye tells to the frog's brain? *Proceedings of the Institut of Radio Engineers*, 47, 1940–1951.
- Luria, A. R. (1966). *Higher cortical functions in man*. New York: Basic Books.
- Luria, A. R. (1970) *Traumatic aphasia*. The Hague: Mouton.
- Luria, A. R. (1976) *Fundamentals of neurolinguistics*. New York: Basic Books.
- Mills, L., & Rollman, G. B. (1979). Left hemisphere selectivity for processing duration in normal subjects. *Brain and Language*, 7, 320–335.
- Massaro, D. W. (1975). Language and information processing. In D. W. Massaro (Ed.) *Understanding language*. New York: Academic Press.
- Merzenich, M. M. & Brugge, J. E. (1973). Representation of the cochlear partition on the superior temporal plane of the macaque monkey. *Brain Research*, 50, 275–296.
- Molfese, D. L., & Erwin, R. J. (1983). An auditory evoked potential study of consonant perception in different vowel environments. *Brain and Language*, 18, 57–70.
- Needham, E. C., & Black, J. W. (1970). The relative ability of aphasic persons to judge the duration and intensity of pure tones. *Journal of Speech and Hearing Research*, 13, 725–730.
- Schwartz, J., & Tallal, P. (1980). Rate of acoustic change may underlie hemispheric specialization for speech perception. *Science*, 207, 1380–1381.
- Seldon, H. L. (1985). The anatomy of the speech perception. In A. Peters, & E. G. Jones (Eds.), *Cerebral cortex*, vol 4: *Association and auditory cortices*. New York: Plenum Press.
- Stevens, S. S. (1974). Perceptual magnitude and its measurement. In E. C. Carterette & M. P. Friedman (Eds.), *Handbook of perception*, vol II: *Psychophysical judgment and measurement*. New York: Academic Press.

- Stevens, S. S. & Volkman, J. (1940). The relation of pitch to frequency: a revised scale. *American Journal of Psychology*, 53, 329–353.
- Studdert-Kennedy, M. (1976). Speech perception. In: N. J. Laas (Ed.) *Contemporary issues in experimental phonetics*. New York: Academic Press.
- Swisher, L., & Hirsh, I. J. (1972). Brain damage and ordering of two temporally successive stimuli. *Neuropsychologia*, 10, 137–152.
- Romani, G. L., Williamson, S. J., Kaufman, L., & Brenner, D. (1982). Characteristics of the human auditory cortex by the neuromagnetic method. *Experimental Brain Research*, 47, 381–393.
- Warren, R. M. (1976). Auditory illusions and perceptual processes. In N. J. Laas (Ed.) *Contemporary issues in experimental phonetics*. New York: Academic Press.