CEREBRAL LATERALIZATION OF PITCH CUES 
IN THE LINGUISTIC SIGNAL

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ABSTRACT

Linguistic analyses of tone and intonation, as well as experimental and clinical studies of pitch in the speech signal, indicate that pitch cues play various roles in language behavior. These different functions, occurring at different levels of grammar, are located along a continuum of linguistic structure from most structured (e.g., tones) to least structured (e.g., voice quality). Hemispheric laterality studies show that highly structured pitch contrasts are associated with left cerebral processing, whereas least structured pitch cues are specialized to the right hemisphere. Intermediate functional roles of pitch, those conveyed on intonation contours, which are made up of intricate mixings of both all-or-none and graded phenomena, are correspondingly ambiguous with respect to laterality. The studies reviewed lead to the conclusion that pitch in the acoustic signal is processed in the brain according to its functional context, properties of which may be specialized in either hemisphere.

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INTRODUCTION

The speech signal, the foundation on which the complexities of phonology, syntax, and semantics in the linguistic utterance are constructed, can be specified by pitch (fundamental frequency and overtones), amplitude (intensity), and duration. This paper focuses on aspects of one of these parameters, pitch, and its relationship to neuropsychological functions. Pitch plays various roles in the speech signal. Linguistic views of the structure and function of pitch cues in language have noted, for example, that, in the speech stream, pitch functions at many "levels," including phonological (tones), lexical (word accent) and syntactic, (sentence and phrase contours). In addition, pitch provides cues for attitudes and emotions. All these levels have different kinds of linguistic structure (Crystal and Quirk, 1964).

Neuropsychological studies in audition and in motor production have shown that different abilities, which involve pitch as an essential feature, are differently processed in the cerebral hemispheres. Hemispheric specialization for processing pitch cues is a function of the kind or degree of linguistic structure observed at
these various levels.

PITCH CUES IN A FUNCTIONAL HIERARCHY

Pitch cues play different roles in a language system. I shall refer to the several roles of pitch in language as occurring at levels of a functional hierarchy. Bolinger, (1964a/1972a), for example, notes that

Voice, purely as voice, plays many parts in communication. It provides the overtones that are the raw material for vowels: determines the difference between certain consonants and certain others, such as /s/ or /z/ or [f] and [v]; most importantly, it is what gives speech its power to ride over noise and carry long distances. Besides these roles...the fundamental pitch of the voice plays others...such as accent, separating discourse into its larger segments, and communicating emotions (pp. 20-21).

Clearly, the domains occupied by pitch in speech are extremely complex. Even the simplest division, "linguistic" versus "nonlinguistic" role of pitch, is uncertain (Crystal, 1969). In his review of prosodic feature systems, Ladefoged finds it unclear which of several proposed prosodic features specify linguistic contrasts and which are paralinguistic phenomena (Ladefoged, 1971).

The first level in a functional hierarchy of pitch in speech - and the least linguistically structured one - is that of voice quality. Pitch parameters at the level of individual physiological differences (vocal tract size, pitch range, etc.) are generally excluded from formal linguistic analysis (Laver, 1968; 1976). The function and importance of individual vocal quality in the communicative process are not understood. Considerable work has been done on voice recognition but little explanatory theory has resulted (see Hecker, 1971). There are reports that jargon aphasics (whose speech is nonsensical) agree that jargon speech samples spoken by themselves are nonsense, when these samples are read to them by another person. However, they claim that the samples make good sense, when the actual sample is played back by tape recording (Zangwill, 1964; Weinstein, 1974). It would be interesting to investigate whether the intonation contour or voice quality differences account primarily for these results. In any case, in this clinical observation, idiolectal prosody is probably a key element in the patient's response.

The next level of functional use of pitch in speech (and closely related to the first, i.e., the personal vocal-trait level) is often called "paralinguistic," signalling personality traits and emotional states in the intonation contour (Abercrombie, 1968; Addington, 1968; Kramer, 1963). The affective function of tone has been seen to reflect individual psychology more than represent features of the language community (Fry, 1969, 1970). Some attempts have been made at analyses of affect in the acoustic signal (Lieberman and Michaels, 1962). Williams and Stevens (1972) found regular patterns of pitch changes associated with anger and fear; and Streeter et al. (1979) found higher pitch levels during deception. Aspects of emotion in the speech signal are known to be associated with right hemisphere functioning. These studies are reviewed below.

Closely related to the affective level, but often analyzed as linguistic, in the sense of having patterns or structure, is the distinguishing of attitudes by intonation, including attitudes toward the speaker himself, toward the remark being spoken, or toward the listener. This is a use of intonation to express a more personal commentary on the sentence being produced. When prosodic features extend over the entire sentence, they express such notions as declarative statement, interrogation, hesitancy, irony. This use of
prosodic parameters is probably universal in human language (Wang, 1971).

The next level, syntactic use of intonation, refers to contrasts between types of sentence, such as question and statement, or types of clauses, such as appositive vs. restrictive. Wang’s examples illustrate one syntactic function of prosody, “to configurate speech into syntactic units of various sizes” and types:

Appositive: The student, who studies Swahili, went to Tanzania.

Restrictive: The student who studied Swahili went to Tanzania.

(The one who didn’t had to stay in Paris)

Lea (1973a,b) observes that many linguists—including Jones (1932), Trager and Smith (1951), Gleason (1956), and Hultzen (1959)—have claimed that intonation indicates the immediate constituent structure of the English sentence (p. 10). Furthermore, experimental studies on the identification of constituent structure on the basis of prosodic cues, indicate that pitch changes are important in cueing constituent structure (Wingfield, 1975; Wingfield and Klein, 1971; Lehiste, 1976; Collier and t’Hart, 1975; Darwin, 1975).

The grammatical or syntactic function of intonation is closely tied to attitude contrasts. Pike (1945) found it necessary to define different intonation contours in terms of attitudes of the speaker:

It was a marked surprise to me to find that there are many different contours which can be used on questions, and that for any contour used on a question I could usually find the same one used on a statement; likewise, for all—or nearly all—contours used on statements, I found the same ones used on questions. In other words, there appeared to be no question pitch as such. This type of evidence is responsible for the necessity of abandoning grammatical or lexical definition of contours; definition in terms of attitudes of the speaker has been utilized, instead, in this study (in Bolinger, 1972a, p. 59).

Crystal (1969) suggests that an intonation pattern “signals different kinds of information simultaneously,” including syntactic, attitudinal, and emotional. These interact with sociolinguistic features (Giles and Powesland, 1975). Some information is more dominant than the rest “in a given percept”, and therefore Crystal advocates a descriptive model which incorporates degrees of attitudinal and grammatical function for any given utterance (pp. 288-289).

Greenberg’s (1969) investigations demonstrated the reality of these “degrees” in comprehension and production of intonation contrasts in listeners and speakers. Greenberg based his studies on a stratified model of intonation “in which certain functions are characterized as overlays upon these earlier (in the generative sense) more basic strata” (p. 3). The test stimuli were made up of intonation contrasts containing syntactic, attitudinal (i.e. emphatic vs. unemphatic) and emotional cues. Subjects were tested for production and comprehension of these contrasts. Results showed that some intonation contrasts were easier to produce and/or to comprehend than others. Emotional and attitudinal cues were more effectively communicated than some syntactic cues. Intersubject differences interacted with contrast-type difficulty in production and comprehension.

The most discretely structured use of pitch lies in the phonological and lexical domains. For example, pitch as a primary cue in stress functions to distinguish some noun-verb pairs in En-
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tance" (Crystal, 1969, p. 203). For his analysis, Crystal concludes that “one must ... expect degrees of grammatical function for intonation: some structures will be intonationally more restricted than others, and some intonation contrasts will be more frequently used for the purpose of making grammatical contrasts than others” (1969, p. 254-5).

In Crystal’s (1969) formulation, all aspects of “non-segmental phonation,” including prosodic systems, paralinguistic systems, and non-linguistic features, are placed along a scale from “most linguistic” to “least linguistic” (p. 131). A similar scale is proposed in this paper for the levels of pitch functions in language, from “most systematically linguistic” to “least systematically linguistic” (Figure 1). In addition to representing linguistic functions for pitch, this scale also accommodates findings from neuropsychological studies, to be described below, which indicate hemispheric specialization for tasks involving pitch parameters. It will be seen that laterization in the cerebral hemisphere for pitch functions toward the left end of the scale are is overwhelmingly to the left hemisphere, while the “least linguistic” incorporations of pitch in the signal are associated with right hemisphere specialization.

LINGUISTIC DESCRIPTIONS OF PITCH

Prosodic features in general (which include combinations of pitch, intensity, and duration) have presented a special challenge to linguistics. Sapir (1921) wrote that “variations in accent, whether of stress or pitch” are “the subtlest of grammatical processes” (pp. 78-9). There remain controversies about the phonetic nature of prosodic units, the existence and classification of tonal units, the nature of contrastive features, and the range of the linguistic (as distinguished from the “non-linguistic”) function of prosodic phenomena in language (see Ladd, 1980 for review).
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These controversies apply both to studies of linguistic tone and to studies of intonation. Regarding tone, Lehen (1973) points out the "number of distinct kinds of underlying representations" that have been proposed for tonal phenomena in various tone languages (p. 117). Similarly, in the case of intonation, many descriptive systems have been proposed, but none is generally accepted (see Crystal, 1969; Greenberg, 1969; Halliday, 1967; Lieberman, 1975; Ladefoged, 1962; Ladd, 1966). Although they develop a system of stress rules, Chomsky and Halle (1968) have omitted pitch from consideration. Nothing is added to the study of the phonetics of intonation, or the levels within the general framework of syntactic and phonological theory as we so far understand it (p. 18).

Some linguists have attempted to show that pitch features differ from other phonological phenomena in essential ways. Crystal (1969) maintains that although not lacking discreteness altogether, "intonational features" are not formally as discrete as phoneme segments. Nor are they "as easy to define and organize into units" (p. 195). Furthermore, as Bolinger (1963a) has pointed out, in addition to being capable of all-or-none contrasts, pitch phenomena differ in that they show gradience. This means that when the basic contrasts are spoken in degrees (pitch height differences), they give "quantitative differences in intended meaning" (p. 12). Pitch in accent and intonation (although not in linguistic tone) can be occasionally associated directly with speech content (of pitch height differences), whereas most other phonological phenomena have a conventional or arbitrary relationship to the meaning expressed.

Phonemic and morphophonemic descriptive models cannot be extended to the analysis of prosody (for discussion see Crystal, 1969). Bolinger (see 1963a) argued persuasively in articles of the 1950's, against the "level-analysis" (Trager and Smith, 1951), that"

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"most systematically linguistic" ← pitch contrasts → "least systematically linguistic"

phonological tone // lexical-type // syntactic / attitudinal / emotional // personal // psychological

EXAMPLE Chinese

Swedish

Thai

Japanese

commonly found

universal

DOMAIN

segment or syllable

word/phrase

phrase/sentence

HEMISPHERIC SPECIALIZATION

****

LEFT ← RIGHT

Figure 1. A hypothetical scale of levels of functional pitch in the speech signal.
prosody cannot be treated like other phonological features, because it is a separate system with unique qualities and different functions. Others disagree for at least some pitch phenomena (e.g., stress, Chomsky and Halle, 1968). Lehiste (1970) has suggested a compromise view: suprasegmentals are features on phonological units, but in order to accommodate this fact, it will be necessary to revise phonological theory, and to reanalyze the relationship of phonological to other linguistic phenomena. Ladd’s (1980) analysis establishes the existence of both all-or-none and gradient phenomena in intonation in English.

Syntactic evidence has been adduced in the claim that “intonation assignment is not a purely phonological process,” with the generative-transformational model (Stockwell, 1972). These arguments claim that intonation contours are dependent on phenomena outside the phonological component (as are certain other so-called phonological phenomena, such as morpheme boundaries and word boundaries). One argument is that intonation assignment is dependent on deep structure configurations (Bresnan, 1971), another that rules for intonation must precede certain syntactic transformations (Pope, 1971). However, Bolinger (1972b) has taken a position against the “syntax-analysts” of intonation processes, maintaining that prosody in English and syntax are “two domains which should be kept apart” (p. 644). Intonation pitch is a separate system, according to Bolinger, determined by “semantic and emotional highlighting,” only casually related to syntactic structure. “Accent should be viewed as independent, directly reflecting the speaker’s intent” (p. 633). Later studies by Greenberg (1975) strongly support this view, showing that semantic novelty overrule syntactic parameters in predicting accent placement. Similarly, for Lieberman (1975) “tune” and text are difficult domains. Furthermore, recent work in speech perception shows that prosody furnishes such important information about word meanings and syntactic structures that listener strategies may lead them to depend more on prosodic than segmental

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information (see Darwin, 1976 for review; Gunter, 1972; Summerfield, 1975).

PROSODY AS UNIVERSAL

Evidence for universality of intonation also differentiates prosodic phenomena from other phonological features. (Lieberman, 1967). About universality, Bolinger (1972a) concludes that “the general characteristics of intonation seem to be shared more broadly than those of any of the other phenomena commonly gathered under the label of language” (p. 315, and Bolinger, 1964b).

Some linguists have ascribed the universality of intonation features in language to physical or psychophysical facts. Lieberman (1968) claimed that a universal “unmarked breathgroup” exists for statement intonation, and that the fall in fundamental frequency is a result of falling subglottal air pressure. This claim has been challenged by Ohala and Hirona (1967 a,b), who demonstrated that laryngeal muscles are active during the production of statements. Lieberman’s later views are that the natural breath group is the one that uses the least muscular control, being structured but not determined by biological constraints (1979). Lieberman claims that “the pattern of fundamental frequency plays a role on signalling the end of a sentence in most, if not all, human languages” (1977, p. 168). Indeed, similarities of intonation contours in unrelated languages of the world suggest that at least some prosodic phenomena in human language are based in “certain underlying physiological or psychological traits” (Bolinger, 1964b, p. 841). It is in this sense that some prosodic phenomena are probably instinctive, or based in species-specific universals, where as other aspects of language are conventional (Bolinger, 1949). Bolinger (1964a/1972a) pictures intonation as a “half-tamed servant of language”: prosodic features serve emotions, will, and the nervous system processes of tension and relaxation (p. 29). It is especially along that zone between the “tamed”
and the "untamed" that the interactions between linguistic structure and the psychophysical factors in pitch phenomena in language are unclear. In a recent review of intonation across languages, Bolinger asserts that intonational shapes with predictable meanings are so widely shared across languages that they must constitute an essential human trait. Whatever the explanation - physiological or genetic - "the fact is that human speakers everywhere do essentially the same things with fundamental pitch" (1978; but see Ladd, 1979).

PROSODY IN SPEECH PRODUCTION AND PERCEPTION

There is evidence in speech errors for the separation of intonational from (other) phonological organization in speech production. Fromkin (1971) concludes from a review of other speech error studies and her own data that "the sentence or phrase stress and overall intonation is generated separately" (p. 43). These data show that "when vowels or syllables or parts of syllables or whole words are substituted or transposed, there is no change in the stress pattern or contour of the sentence" (p. 42). This fixed overall contour is produced according to the syntactic structure of the utterance, and therefore in a model of speech production, syntactic-semantic features logically precede the intonation-contour generator.

Intonation processing differences are seen in another parameter, in a distinction between holistic and structurally-formulated phrases. In his work of few decades ago, Jespersen (1965, 1969) distinguished between formulas and free expressions in speech production. He claimed that formulas are produced as whole units, --- they "spring into a speaker's mind all at once," whereas free expressions are newly created (1965, p. 26). Furthermore in producing formulas, according to Jespersen, "everything is fixed: you cannot even change the stress," in contrast to free expressions, which can be produced on various intonation contours (p. 18). Crystal (1975) similarly has suggested that the intonation contours of conventional phrases are fixed, in contrast to structurally formulated utterances. A psycholinguistic study investigating subjects' abilities to identify differences between free and fixed expressions was conducted by Van Lancker and Canter (1980). "Ditropic" sentences --- sentences ambiguous in having either a literal or an idiomatic interpretation (such as David spilled the beans) --- were selected and prepared for a series of tests. Subjects were generally unable to discriminate between idiomatically and literally intended utterances when hearing them excised from paragraph context. However, subjects were able to interpret the correct meanings of idiomatic and literal versions of ditropic sentences, when they had been recorded in contrastive pairs by speakers intending to communicate the two meanings. Acoustic measurements of these utterances revealed that besides being longer than their counterpart idioms, the literals contained more discrete pitch contours. The idioms, in contrast, are on intonation contours that are smoother than are seen in the literals (Van Lancker, Canter, and Terbeek, 1980). This finding supports the suggestions above found in the literature. The evidence is that pitch contours in production and perception are used at least in part as cues to types of meaning (see also Bolinger, 1965). As reviewed above, perceptual studies have shown that pitch and intonation contours are crucial to perception of constituent structure (Wingfield and Klein, 1971; Nooteboom et al., 1973; Bolinger, 1978), attitudinal meanings (Scherer, 1974); emotional meanings (Williams and Stevens, 1972; Davitz and Davitz, 1974), and pragmatic meanings (Duncan, 1972, 1974).

PROSODY IN LANGUAGE ACQUISITION

Intonation abilities in production and perception are observed early in the infant (Benda, 1967; Kaplan, 1970). Mimicry of intonation in speech has been observed in 10-month and 13-month old infants (Pike, 1949; Lieberman, 1968; Ervin-Tripp, 1966; Kaplan and Kaplan, 1971). Babies distinguish friendly from unfriendly voices at
Evidence suggests that singing and speaking are separate abilities. The idea that they are separate is based on observations in stuttering and in brain damage. Severe stuttersers are able to sing words normally; aphasics can often sing well when they can hardly speak. Performance abilities for singing differ in aphasia. Dysfluent aphasics can often sing melodies on ah or la; some can sing words when prompted; others are able to sing lyrics of old songs and of newly learned songs. Pitch production ability can vary according to production mode. I observed a patient who read aloud on a monotone, as though only very small range of pitches were available to him; but who then could sing melodies on la with ease. Another patient spoke the words Look inside and see fluently, but was unable to use other speech to form utterances, with the exception of a few automatic phrases. Later testing revealed that this patient knew a song with these exact lyrics, which she could sing with ease. Evidence is strong that automatic speech and singing are subserved by the intact right hemisphere (Kinsbourne, 1971; Czopf, 1980), as is aphasias comprehension (Pettit, 1979; Pettit and Noll, 1972).

Even more dramatic evidence comes from left hemispherectomy patients, who use appropriate intonation in the automatic phrases remaining to them (Crockett and Estridge, 1951; Zollinger, 1935). One such adult case, with a severe expressive aphasia, could sing with normal articulation of lyrics (Smith, 1966). Another left hemispherectomy patient, whose speech was severely impaired, sang "Jingle Bells" fluently on her own (Gordon, 1973). Using the Wada technique in which each cerebral hemisphere is temporally anesthetized, Bogen and Gordon (1971) demonstrated that a patient was able to sing better than speak while her left hemisphere was infused and, conversely, could speak with more facility than she could sing during temporary anesthetization of the right cerebral hemisphere.

Aphasiologists have observed the relationship between singing and nonpropositional subsets of speech. Kriender and Fradis
By repetition, on a rhythmic musical and emotional background, of words or word-sets contained in songs, reinforced by visual perception of corresponding images and words, as well as by patients singing the texts previously heard, an easier reactivation of impaired speech function can be obtained in any form of aphasia (p. 145).

The melodic intonation therapy technique has been used with some success in severe aphasia. The patient first sings sentences, and then learns to produce the expression with pitch contours increasingly resembling normal speech intonation (Sparks, Helm and Albert, 1973). The patient responds with an exaggerated melodic contour, which need not be exactly equivalent to the therapist's pattern. In this task the patient is attempting to imitate melodies which are chosen from a repertory of known melody-types. The therapy is based on the notion that standard melodies and well-learned songs are sometimes available to the aphasic, even when fluent speech is not.

Goldstein (1948) suggests that the difference between singing and speaking "is due to the different physiological and psychological structures of both performances" (p. 146). However, his distinction is actually between singing and propositional use of language. In contrast, he assumes a connection between singing and nonpropositional modes:

According to the more primitive character of singing and the close relationship of singing to expressive movements and to emotional language, it can be assumed that in brain damage, singing will be preserved longer than language. (Thus the preservation of singing might be explainable) in the same way as the better preservation of emotional language. In this respect, there is significance in the frequent parallelism between preservation of singing and other emotional expressions, such as the Lord's Prayer. (Furthermore)... there is possibility that this automatized performance may be guaranteed by the function of the minor hemisphere (p. 147).

In many aphasic patients with stereotyped utterances, the first stage of recovery involves recovering the ability to produce intonation contours. The patient typically remains limited to the stereotyped phrase, but begins to show improvement when the "manner of utterance and the intonation are first modified." The patient begins to show a "differentiated organization of the permanent verbal stereotype," producing the same identical item, but produced with varieties of intonation and speech (Alajouanine, 1956). Critchley (1970) notes that the new words produced by a recovering aphasic occur in staccato monotone, unlike the "melodious recurring utterance" comprising the automatic repertory (stereotyped phrases). A typical "monophasic" patient used the phrase on the booz to reply to questions and to speak spontaneously. By use of intonation and gesture "he was able to utilize these three words with such success as to make them express his immediate desires or to signify assent, negation or dismissal" (p. 206).

The fact that intonation is separable from other phonological output is striking in phonological jargon aphasia. In semantic jargon aphasia, well-formed words occur but the overall utterances are nonsense. There is a dissociation between sound and meaning. In addition to the sound/meaning breakdown, other kinds of jargon contain neologisms and literal paraphasias, producing a stream of non-words (Green, 1969). In these kinds, the
phonemes remain intact; the phonological output is impaired at a level of abstract representation. The dissociation in jargon aphasias between semantic and phonemic paraphasias suggests that the “functional systems corresponding to the phonemic structure of linguistic elements and those underlying the semantic values are different and can be selectively damaged” (Alajouanine and Lhermitte, 1964, p. 177). Yet both types of jargon aphasias are associated with good rhythm and intonation, which demonstrates the autonomy of these prosodic parameters. Thus it is frequently the case that in aphasia the melodic patterns are intact, but the syntactic structures are not (because only one holistic phrase is spoken by the patient, for example). This common occurrence led the aphasologist (Pick, 1913) to propose a model of speech production which separates intonation from other grammatical processes. The model consists of a “nonverbal” phase, which includes the melodic pattern and rhythm in the intended utterance, followed by the “verbal” phase including positioning of words and use of grammatical processes.

This model is similar to the production model proposed by Fromkin (1971) discussed above.

Defect of intonation (dysprosody) is rare in aphasic conditions (Pick, 1973; but see Monrad-Krohn, 1947 a,b,c; 1957; 1963; Kent, 1979). Such disturbances, when they occur in aphasics, are likely due to concomitant subcortical injury. Nonaphasic monotone speech, somewhat more common, has been attributed to lesions of the brain stem, specifically of the basal ganglia (Lenneberg, 1967).

Pick attributes the rarity of intonation disturbance, defective accentuation, and monotony to the “fact that intonation is a very early acquisition, preceding articulate speech and, therefore, is an especially automatized achievement. Moreover, since intonation stems from emotional life, it is per se a more primitive feature” (1973). Pick’s remarks are based on clinical observations that aphasic patients correctly use intonation contours to express emotions, whereas other sorts of verbal expression are lacking. His view of intonation, however, is not very far from Bolinger’s (1964a/1972a), for whom all of intonation is based in the “tides of emotion.” The “tides” are similar across language and they are first-learned in children. Intonation in language can get a foothold in the syntax. “But the foothold is with one foot; the other one is back there doing its primitive dance” (1964b, p. 844).

The few reports of dysprosody are difficult to interpret, because the linguistic description is lacking, or difficult to assess in terms of linguistic features. Some cases of a “foreign accent” as a result of aphasic disturbance have been reported (Ustvedt, 1937; DeRueck and O’Conner, 1964; Cole, 1971; Whitaker, 1975; Van Lancker et al., 1980, Whitty, 1964). There is one well-known report of a Norwegian woman who lost the phonemic distinction between two intonations (phonemic in her language) but retained the pitch contours in her speech (Monrad-Krohn, 1947a). As a consequence, she was mistaken for a German in Nazi-occupied territory. It is possible that these defects are not in the production of intonation, but of rhythmic patterning, or timing in speech performance. A number of studies of stress and intonation processing in aphasia have been cited in a compilation by McMahon (1972): Calvi, 1963; Fink, 1969; Mihailetscu, et al., 1970; and Schveiger, 1968.

A study by Blumstein and Goodglass (1972) demonstrated that aphasics (Broca’s and fluent aphasics) could distinguish between items in pairs of words that differed primarily in stress (syllable length and vowel quality are also involved to some extent in some cases). Sample pairs were white cap and whitecap; convict and convet. Aphasics (both groups) could discriminate
stress contrasts, and although they made more overall errors than the normals, the pattern of errors was the same in both aphasics and normals. The results of the study suggest that the perception of stress is preserved in aphasia. The authors conclude that “stress recognition appears to be a remarkably robust linguistic feature” (p. 806). The results were the same for aphasics with good and with poor comprehension of speech.

The acoustic correlates of stress are fundamental frequency (pitch), duration, and intensity (amplitude). According to studies by Bolinger (1965) on normal and synthetic speech, the primary acoustic cue in stress accent is pitch prominence. Fry (1955, 1958) demonstrated that intensity difference alone cannot serve as cues for stress placement. A number of other studies on various languages have shown that fundamental frequency is the primary acoustic correlate for perceived stress (see Lehiste, 1970 for review). Therefore the findings of Blumstein and Goodglass (1972) suggest, more specifically, that aphasics (even those with poor overall speech comprehension) retain the ability to process pitch distinctions when these distinctions are used in a set of linguistic contrasts.

A recent study of the prosodic parameters of Broca’s aphasia indicated that the pitch contours were preserved in the two-word utterances; but that the segmental lengthening observed in normal phrasing was abnormal in the aphasic speech (Danly et al., 1979). Thus it is the temporal structure and not the pitch contour that contributes to the characteristic “dysprosody” described for Broca’s aphasia (see Goodglass et al., 1967).

In contrast, a similar investigation revealed abnormal pitch contours in the speech of Wernicke’s aphasia (Cooper, et al., 1979). However, the study upheld the notion of the independence of pitch phenomena of the other components of the speech signal --- the unique declinations of the fundamental frequency observed in Wernicke’s speech were not affected by their literal paraphasias. This fact suggested to the investigators that programming of intonation contour proceeds independently of phoneme selection.

Under what conditions tones in a tone language are better retained in aphasia than other phonological features, or than other pitch phenomena in language, is a question of great interest. There is one report that tone contrasts were retained by a speaker of a tone language who became aphasic: Dr. Lyman in Peiping observed that one Chinese aphasic correctly retained tonal inflections, despite a restricted vocabulary, according to Critchley (1970). Only if dysarthria is also present are the tones distorted. However, there are reportedly some Chinese aphasics with tone problems. In a recent careful study, Naeser and Chan (1979) described a native speaker of Mandarin who was impaired in both recognition and perception of tone contrasts in her language following damage to the left hemisphere.

Complementary to the findings that abilities relying on pitch processing are often retained in left hemisphere damaged patients are findings for deficits associated with damage to the right hemisphere. Ross and Mesulam (1979) have reported on two patients who lost the ability to inflect their speech with appropriate attitudinal and emotional quality, as a result of right hemisphere lesions. In a study by Heilman et al. (1975), patients with right hemisphere lesions were defective in comprehending the “emotional mood” of spoken sentences. A later study by Tucker et al. (1977) demonstrated that patients with right hemisphere disease were significantly poorer at recognizing, discriminating, and expressing affectively intoned speech. Assal et al. (1976) have demonstrated deficits in voice quality and emotional tone recognition in patients with right hemisphere brain damage.
CEREBRAL LATERALIZATION OF PITCH PROCESSING IN CEREBRAL FUNCTION

The neurophysiological substrates for bilaterality of pitch processing in both production and comprehension are present in the normal brain (Kaplan, 1960). In particular, each hemisphere is capable of controlling the larynx and articulatory musculature for production of pitch, tone, and intonation. Motor sources of speech (for phonation and articulation) are bilaterally represented in the primary and supplementary motor areas on the cortex; faciovocal activity is subcortically represented in animals (Kelly et al., 1946; Robinson, 1967 a, b). In humans, there are four cortical areas which, when stimulated by an electric current at surgery, cause the patient to emit a vowel-like phonation: the precentral Rolandic gyrus of both hemispheres, and the supplementary motor area of both hemispheres (Penfield and Roberts, 1959). Thus vocalization can be initiated by electrode stimulation of either hemisphere, and specifically at points anterior to the speech center.

It is also Goldstein’s view that both phonation and articulation of speech gestures are bilaterally represented.

Even though there can be no doubt that, for the right-handed person, the left hemisphere is of paramount significance for language, it must be noted that for the formation of sounds the corresponding area of the other hemisphere may play an important part, different in individual cases ... With regard to the bilateral speech movements...there is a close relationship between the two motor speech areas (1948, p. 202).

Penfield and Roberts (1959) point out as further evidence that the motor sources for speech are bilaterally represented, that if the Rolandic motor strip of one hemisphere is destroyed, the other one takes over. They claim that “cortical control of the voice, including articulatory movements and vocalization” can be served by either hemisphere alone. Excision of the lower Rolandic motor cortex (face, jaws, tongue, and throat) on either side only temporarily produces dysarthria or thickness of speech, which usually recovers fully to normal speech. “It seems likely that such a patient is able to speak (after removal of the lower portion of the Rolandic strip) by employment of the cortical motor mechanism of the other hemisphere” (p. 16). Nondominant hemispherectomies have not resulted in impaired speech (Smith and Buckland, 1967; Smith, 1969). Hagen (1971) reports that three right hemisphere patients sustained only minimal dysarthria four weeks after removal of their entire right hemisphere. Vocalization by the right hemisphere of a split-brain patient has also been reported (Butler and Norrussel, 1968).

Both hemispheres are equipotential for pitch discrimination. Experiments on the auditory systems of animals have not demonstrated hemispheric differences in audition (Neff, 1962). Instead, the only kind of auditory discrimination impaired by unilateral temporal lobe ablation in cats is sound localization, a complex task requiring interaction between inputs at both ears. The auditory pathways from the organ of Corti (in the cochlea of the ear) to the auditory cortex have been investigated in detail. Each ear projects to both auditory receiving areas in the cortex (by ipsilateral and contralateral pathways). The asymmetry in projections from each ear to the auditory cortices has been observed in records of gross evoked responses to click stimulation recorded from the auditory areas of the right and left hemispheres (R. Thompson, 1967). Tunturi (1946) and Rosenzweig (1951, 1954) demonstrated that the amplitude of the evoked response is greater at the cortical area contralateral to the ear stimu-
Cerebral Lateralization of Pitch Cues in the Linguistic Signal

sounds required patients with right or left brain damage to listen to tape-recorded words, and respond by pointing to one of four pictures on a card. Both groups (right and left hemisphere damage) performed worse than controls on a test of nonverbal meaningful sound discrimination. However, subjects with left-hemisphere lesions, especially in posterior regions, performed significantly worse than the control group on the test of verbal sound discrimination. Similarly, a right hemisphere superiority for perceiving music has been demonstrated in lobectomized patients. Subjects of listening tasks who previously had their right temporal lobes removed did worse than left lobectomy patients on the Timbre and Tonal Memory subtest of the Seashore Test of Musical Abilities (Milner, 1962), and on recognizing orchestrated melodies (Shankweiler, 1966).

It has been claimed that singing and music perception are capacities of the right hemisphere (Henschel, 1926; Luria, 1966). These abilities may be bilaterally represented (see review in Bogen, 1969 a,b, p. 144). Observations in patients with left-hemispherectomies have confirmed the early belief that the right hemisphere is capable of motor control for singing words (Smith, 1966, 1972). Two left hemispherectomy patients were able to recall and sing songs (with their lyrics) suggesting that the right hemisphere may play a significant role in "musical memory" and in the "neuromotor processes of singing," each of which involves many of the same mechanisms of vocalization and articulation used in spoken languages. Studies on six patients using the Wada technique to determine hemispheric dominance were conducted by Bogen and Gordon (1971). They conclude that the "right hemisphere is more important for singing than speech," and that the right is specialized for "tonal abilities." Similarly, in their review of recent work in lateralization of musical and verbal abilities, Demasio and Demasio (1977) conclude that the musical faculty and dominance for language are not intimately related; and furthermore,
that the right hemisphere is probably dominant for musical execution, while musical perception may be associated with "variable dominance." This dissociation between music and speech processing has been demonstrated experimentally by Goodglass and Calderon (1977).

DICHOTIC LISTENING STUDIES AND PITCH PROCESSING

As reviewed above, neuroanatomical and behavioral evidence suggests that simple pitch processing abilities are bilaterally and/or subcortically represented in the brain. However, hemispheric specialization for pitch processing within different tasks has been observed in humans. Specialization to one or the other hemisphere is determined not alone by the acoustic signal, but by its function, or by principles of its organization in a complex signal (see Springer, 1977). According to the functional interpretation of hemispheric specialization for incoming stimuli, a stimulus is lateralized (or not) to either hemisphere depending on the functional context of the stimulus in any given task. In fact, "degrees" of asymmetry may be posited to model the results of clinical and experimental studies (Berlin, 1977; Cullen et al., 1974). Furthermore, a common denominator may underlie the class of tasks specialized in the one hemisphere, different from the common characteristics underlying tasks lateralized into the other hemisphere. That is, there may be distinct modes of processing intrinsic to each cerebral hemisphere. As Kimura (1967) outlined,

dichotic listening provides a means for studying further the division of labour between the left and right hemispheres of the brain. By varying the stimulus dimensions, we may be able to define more explicitly just what characteristics differentiate stimuli depending more for their perception on the

left hemisphere, from those depending more on the right hemisphere. That is, we can ask which stimulus characteristics are associated with a right- or a left-ear superiority (p. 173).

The neurolinguistic approach focuses this kind of research plan on the processing of language. There is evidence that language is heterogeneously processed in the brain (some linguistic phenomena are lateralized in the left hemisphere, some are not) (Van Lancker, 1973). If it is also true that there are modes of processing unique to each hemisphere, then it may be useful for linguistic analysis to sort out classes of "left-lateralized" linguistic phenomena, and establish the unique characteristics or properties which underlie them. It is in this spirit that appropriate experiments are described here to demonstrate that pitch is processed differently in the brain from other parameters in the linguistic signal; and that different pitch cues within the signal are differentially processed in the brain. In fact, dichotic listening studies have repeatedly demonstrated that pitch cues are processed in the left or right hemisphere, depending on the nature of the overall stimulus in which the pitch cues are embodied.

In dichotic listening, a subject wearing stereo headphones is presented with two acoustic stimuli at the same time, one at each ear. Subjects usually make more correct identifications at one ear than the other. A variety of stimuli have been tested. As reviewed in the previous section, ears project fibers to the left and right auditory receiving areas at the cortex. The contralateral connections from ear to cortex (right ear to left temporal lobe, left ear to right temporal lobe) are stronger than the ipsilateral connections. Both neuroanatomical and behavioral observations lead to the conclusion that ear superiority in dichotic listening is due to specialized abilities of the contralateral hemisphere.
In dichotic listening, most linguistic stimuli produce a right ear advantage (REA -- more correct identifications at the right ear) in right-handed subjects. The right ear advantage (REA) has remained constant over various experimental conditions. It is not cancelled by attention factors (Bryden, 1969; Myers, 1971), by changed orders of report (Bryden, 1963, 1967), by response mode, whether verbal, written, or button-pressing (Springer, 1971, 1972), by the "lag effect" (lagging one stimulus behind the other) (Kirstein, 1970), or by requiring a temporal order judgement (Day, Cutting and Copeland, 1971).

Investigators have demonstrated a right ear superiority for dichotically presented consonant-vowel syllables (Studdert-Kennedy and Shankweiler, 1970; Darwin, 1971; Berlin et al., 1972 a, b; 1973 a, b); digits (Broadbent, 1954; Kimura, 1961); words (Haggard, 1971); including nonsense words (Curry, 1967), function words (Curry and Rutherford, 1967), and nouns (Borkowsky, Spren, and Stutz, 1965; Pettit and Noll, 1972) backwards speech (Kimura and Folb, 1968); rhythmic patterns (Robinson and Solomon, 1974); Morse Code signals (Papcun et al., 1971, 1974); sentences (Zurif and Sait, 1969); for melody (Gordon, 1975; Johnson, 1977) and especially rhythmic elements of melody (Gordon, 1978); and linguistic tones carried on words in a tone-language (Van Lancker and Fromkin, 1973). In one study, a production-mode adaptation of dichotic listening gave a laterality effect for lingual tracking of tones: a right ear advantage when the feedback (cursor) tone was in the right ear, while the target tone was in the left ear (Sussman, 1971, Sussman and MacNeilage, 1975). Secondly, Morse code dot-dash sequences yielded a right ear effect not only in a linguistic task (in experienced Morse code operators), but also as a nonlinguistic task (7 units or less in naive subjects) (Papcun et al., 1971, 1974).

Most of the results are covered by the generalization that the left hemisphere is specialized for linguistic processing. For the cursor/target tone study, the notion "articulability" serves to accommodate these findings, because the ear effect was found only when the tongue (not the hand) tracked the tone. For the Morse code findings, specialized abilities for processing of "sequential subparts" (within a 7 unit span) in the left hemisphere can be invoked to explain the results. These interpretations claim that the language is subsumed under more general processing abilities which characterize left hemisphere specialization: a specialization for the analysis and organization of vocally articulable sounds, (Berlin, 1973b) and/or a specialization for sequential processing (Papcun et al. 1974, Bogen, 1969a,b) or temporal processing (Efron, 1963a, b; Carmon and Nachshon, 1971; Gordon, 1973).

Perceptual evidence suggests that some pitch processing is not specialized in either hemisphere. Neither ear was preferred in the processing of clicks (Schulhoff and Goodglass, 1969) or steady-state vowels (Shankweiler and Studdert-Kennedy, 1967). Darwin's studies show that although some types of pitch changes are more successfully recognized by the left ear (right hemisphere), analysis of simple pitch contours can be done in either hemisphere (1969, p. 168). Milner (1962) found no significant change in pitch perception after unilateral lobectomy (left or right). Zurif and Mendelsohn, in their dichotic listening tests for sentences, are led to suggest the possibility that "a preliminary and partial analysis of prosodic contours can be carried out in both hemispheres" (1972, p. 331). Blumstein and Cooper (1974) found no ear effect in certain of their stimulus conditions in dichotic presentation of intonation contours. Curry (1968) found no difference in performance for the dichotic pitch discrimination test in normals and a right hemisphere-rectomized patient. On the basis of the patient's high scores on both monotic and dichotic pitch discrimination tasks, (higher than normal subjects' scores) and previous findings that cats can make pitch discriminations after bilateral ablutions of the
cortex (Katsuki, 1961, 1962; Butler et al., 1957) it is suggested that pitch is subcortically processed. Some studies have shown a lack of ear effect for processing of vowels (Shankweiler and Studdert-Kennedy, 1967; Studdert-Kennedy and Shankweiler, 1970). In a reduced right ear advantage for fricatives (Darwin, 1971, 1973) and glides (Cutting, 1972, 1973, 1974a,b; Day and Vigorito, 1973; Haggard, 1969, 1971). A study by Sidtis (1980) showed that pure tones resulted in no hemispheric preference in an A-B-X choice reaction time procedure, whereas pitch stimuli with one or more overtones included in the signal gave increasingly higher accuracies and an increasing right hemisphere advantage. The best performances were on the most complex tones (odd harmonics only——“square waves”); these also showed the strongest ear advantage. The findings that shortening vowel stimuli or introducing noise results in a right ear advantage (Weiss and House, 1973; Godfrey, 1974), which is not observed in vowel stimuli presented alone, may be explained by the observation by Sidtis that increased harmonic information enhances right hemispheric preference.

Other sounds have produced a left ear (right hemisphere) superiority, especially various kinds of musical stimuli such as baroque melodies (Kimura, 1964), chords (Gordon, 1970, 1975), and tone pulses (Spellacy, 1970). Darwin (1969) reported a slight left ear advantage for dichotically presented pitch contours, in four stimulus conditions: on a syllable ti, on a single formant, in discrete steps, and glissando. In other dichotic listening studies, left ear advantage resulted for environmental sounds (Curry, 1967), sonor signals (Chaney and Webster, 1966), non-language vocalizations such as sobs and chuckles (Carmon and Nachshon, 1973), hummed melodies (King and Kimura, 1972), and the “emotional tone” of sentences (Parkinson, 1970; Haggard and Parkinson, 1971). Leder and Baker (1978) found no ear difference in a dichotic listening task that presented three monosyllabic sentences with four different intoned contours (declarative; interrogative; imperative; and conditional) to twenty subjects. Wolff (1977) found no differences in auditory memory for fundamental frequency differences on CV syllables between left and right hemispheres. Blumstein and Cooper (1973) found a slight left ear advantage or no ear advantage, for intonation contours filtered from real speech, and intonation contours carried in a nonsense syllable medium. The left ear advantage resulted even when subjects were asked to identify the stimuli by sentence-type. These authors suggest that “the right hemisphere is directly involved in the perception of intonation contours, and that normal language perception may involve the active participation of both cerebral hemispheres.” Wingfield’s (1975) studies show that intonation patterns continue to cue sentence structure under conditions of acoustic distortion such that words are unrecognizable, and stress and timing have been compressed, indicating that prosodic features are the “most resistant parts of the waveform.” This observation may be related to the fact that more of the brain participates in the processing of prosody.

As reviewed above, some studies have already exemplified the verbal-nonverbal dichotomy for dichotic listening of different sounds. For example, Curry’s (1967) group of normal subjects showed a right ear superiority for a dichotic word test and nonsense word test; a nonsignificant left ear superiority in a dichotic pitch discrimination test, and a left ear effect for an environmental sounds test. Similarly, in some studies, pitch-processing shows laterality effects according to task (see Zurif, 1974 for review). This set-influence effect is exemplified by Spellacy and Blumstein (1970), who showed that vowels in a linguistic context were better recognized by the right ear, while the same stimuli in a non-language context (embedded in music and environmental sounds) were preferred by the left ear. Similarly, when pitch was used linguistically to distinguish voiceless from voiced consonants, a right ear advantage resulted (Haggard and Parkinson, 1971). Studies by Day, Cutting and Copeland (1971) have demonstrated that dichotic stimuli processed in terms of a lin-
guistic dimension are better heard at the right ear, although the same stimuli, processed according to a non-linguistic dimension, pitch, are preferred by the left ear. This verbal-nonverbal dichotomy for acoustic processing in the left versus the right hemisphere has been further confirmed by evoked cortical response studies (Wood, Goff and Day, 1971; Cohn, 1971). A reaction-time study using binaurally presented stimuli provided further evidence that different mechanisms underlie the processing of linguistic as compared with nonlinguistic dimensions of same stimuli (Day and Wood, 1971). Practice in a task of dichotically presented nouns and piano tones resulted in the expected effects of a right ear advantage for the nouns, left ear advantage for the tones (Sidtis, and Bryden, 1978); Gates and Bradshaw (1977) showed a right ear advantage for unfamiliar melodies and a left ear advantage for familiar melodies.

A dichotic listening study using stimuli from a tone language, Thai, strongly confirmed the functional theory of hemispheric specialization (Van Lancker and Fromkin, 1973). In a tone language, pitch alone may contrast the meanings of words which are otherwise identical in segmental sounds. In a non-tone language, such as English, pitch is used to convey syntactic and semantic information, but the meaning of cat will remain the same whether it is produced with a high, medium, low, rising or falling pitch in a sentence such as The cat is on the mat. In Thai, however, (or in languages such as Chinese, Twi, Hausa, etc.) a word like mat will mean different things depending on the pitch (See Table 1).

For the dichotic listening study, three audio tapes were prepared using stimuli produced by a female native Thai speaker. The stimuli were three kinds: 1) five Thai words differing only in tone (the tone-word stimuli); 2) five Thai words contrasting only in initial consonant-word stimuli, all occurring on mid-tone; 3) and five hums produced by humming the five Thai tone contrasts (Table 1).

Cerebral Lateralization of Pitch Cues in the Linguistic Signal

The results from 23 right-handed native Thai speakers as subjects revealed a significant right ear effect for tone-words* and consonant-words, but no ear effects for hums. Thai speakers were processing the pitch contrasts on tone-words and on consonant-words as language, and were therefore engaging the left hemisphere for these two tasks. The hums yielded no significant ear effects because they were not linguistically structured (although containing the same contrasts as the tones).

Further analyses of the data were done to compare results from the three different conditions, tone-word, consonant-words, and hums.

First, the right ear superiority for tone-words and consonant-words were compared. Using the Percentage of Errors (POE) method of analyzing dichotic listening results (Harshman and Krashen, 1972), error totals were converted to POE scores. For Thai subjects, the overall POE (percentage of errors made by the left ear) mean for tone words was 57.3, for consonant words 56.4, for hums, 50.8. The mean for individual subject POE scored for tones was 58.7, for consonant words, the mean POE score was 58.5, for hums, 48.6. A matched-pairs T-test showed no significant difference in between Tone-word and Consonant-word sets ($T= .576$).

In contrast, individual comparisons of ear superiority results for consonant-words and hums, and tone-words and hums reveal larger numbers of subjects with nonparallel trends. For tone-words and hums, eight subjects had right ear advantages for both tasks, two subjects had left ear advantages for both tasks, ten had trends in opposite directions, and two had no ear effect on one or the other task. For consonant-words and the hums, seven had a right ear advantage for both tasks, three had left ear advantages, and twelve were opposite or inconsistent (Table 2).
(1) Tone-words

<table>
<thead>
<tr>
<th>Stimulus</th>
<th>Tone</th>
<th>Length (ms)</th>
<th>English gloss</th>
</tr>
</thead>
<tbody>
<tr>
<td>nää</td>
<td>mid tone</td>
<td>625</td>
<td>“field”</td>
</tr>
<tr>
<td>nàa</td>
<td>low tone</td>
<td>650</td>
<td>(a nickname)</td>
</tr>
<tr>
<td>nāa</td>
<td>falling</td>
<td>575</td>
<td>“face”</td>
</tr>
<tr>
<td>nāa</td>
<td>high tone</td>
<td>625</td>
<td>“aunt”</td>
</tr>
<tr>
<td>nāa</td>
<td>rising</td>
<td>650</td>
<td>“thick”</td>
</tr>
</tbody>
</table>

(2) Consonant-words

<table>
<thead>
<tr>
<th>Consonant</th>
<th>Tone</th>
<th>Length (ms)</th>
<th>English gloss</th>
</tr>
</thead>
<tbody>
<tr>
<td>dāa</td>
<td>mid tone</td>
<td>700</td>
<td>(a nickname)</td>
</tr>
<tr>
<td>nāa</td>
<td>mid tone</td>
<td>650</td>
<td>“field”</td>
</tr>
<tr>
<td>sāa</td>
<td>mid tone</td>
<td>650</td>
<td>“diminish”</td>
</tr>
<tr>
<td>cāa</td>
<td>mid tone</td>
<td>650</td>
<td>“tea”</td>
</tr>
<tr>
<td>lāa</td>
<td>mid tone</td>
<td>650</td>
<td>“goodbye”</td>
</tr>
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</table>

(3) Hums

<table>
<thead>
<tr>
<th>Hums</th>
<th>Tone</th>
<th>Length (ms)</th>
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</thead>
<tbody>
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<td>falling</td>
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<td></td>
<td>high tone</td>
<td>575</td>
</tr>
<tr>
<td></td>
<td>rising</td>
<td>525</td>
</tr>
</tbody>
</table>

Table 1. 3 sets of stimuli used

Cerebral Lateralization of Pitch Cues in the Linguistic Signal

From these figures, it seems that in the Thai-speakers, the tone-words and the consonant-words were processed similarly. A fact about handedness tends to support this conclusion. All subjects described themselves as right-handed, but one of the three with a left ear advantage on both consonant-words and tone-words was reportedly also “somewhat ambidextrous.” (Thai children are encouraged to use their right hands even if they would have preferred the left.)

Data for individual subjects (N=22) in the Thai dichotic listening were analyzed. For the tone-word condition, 17 of 22 subjects showed a right ear advantage (a higher percentage of errors at the left ear), four showed a left ear advantage, and one showed no ear difference. These results are significantly different in a Chi-Square test from a theoretical distribution of right and left ear scores at \( p < .02 \). For consonant-words, fifteen out of 22 Thai subjects showed a right ear advantage, five a left ear advantage, and 2 showed no ear preference. These results tend to be significant \( p < .10 \). For hums, ten Thai subjects had a right ear advantage, ten a left ear advantage, and one had no ear advantage.

Another observation in individual subjects' performances suggests that tone-words and consonant-words were being processed similarly. Of 22 subjects, eighteen had ear advantages in the same direction for both stimulus sets. Fourteen had a right ear advantage for both tone-word and consonant-word stimulus sets, three had a left ear advantage for both stimulus sets, and one had no ear advantage for both sets.

Correlational statistics of individual subjects' scores further support the conclusion that tone-words and consonant-words are processed similarly. Correlation coefficients on 22 Thai subjects are presented in Table 3. Not only are performances for tone-words and consonant-words correlated, but so also are performances for tone-words and hums. An interpretation of these observations in the con-
<table>
<thead>
<tr>
<th></th>
<th>Tone-words</th>
<th>Consonant-words</th>
<th>Hums</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tone-words</td>
<td>.383</td>
<td>.472*</td>
<td></td>
</tr>
<tr>
<td>Consonant-words</td>
<td>.479*</td>
<td>.071</td>
<td></td>
</tr>
<tr>
<td>Hums</td>
<td>.568*</td>
<td>.085</td>
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Pearson’s r
Critical Value for
p < .05 = .423

Spearman’s rho Critical Value for
p < .05 = .450

Table 3. Correlation matrix for compared performance across tasks: Thai subjects.

Table 2. Same-ear advantages across two tasks.
text of cerebral processing of these stimuli might be that the consonant-words and tone-words have in common lateralization of function; they share hemispheric locus by virtue of their function as structured linguistic contrasts. In contrast, the tone-words and hums may have in common a processing ability for pitch phenomena, not related to laterality. This interpretation is consistent with other findings in lateralization research. A schematic representation of the shared properties in the three stimulus tasks is given in Figure 2.

A second experiment was conducted to determine whether a similar result would be obtained using subjects who were not native speakers of a tone language, but who were musically trained. The question was whether the right ear effect in the Thai subjects was actually due to the linguistic system of these speakers, or whether it could have been due to greater familiarity with pitch contrasts. Our interest in investigating this aspect of tone processing was enhanced by a recent finding of Bever and Chiarello (1974) who reported that musically trained subjects recognized melodies better at their right ear, whereas untrained subjects demonstrated the usual left ear advantage for musical sounds (in a monaural listening task). These authors suggested that musical training may have "real neurological concomitants" in requiring different strategies which engage the left hemisphere for otherwise right hemisphere tasks. Forty right-handed male native English speakers served as subjects, divided into two groups with respect to musical training. The musically untrained group had had no formal musical training in the past ten years and had four years or less total exposure. Nearly all had had zero to one year in elementary school and no musical activity since. The musically trained subjects had had at least eight years formal training, some as many as 40 years active participation. Most were currently playing an instrument or singing in a chorus.

For both untrained and trained subjects, a Wilcoxon signed ranks test on total errors (counting wrong answers and ear location
errors, which we called intrusions) yielded a significant difference between ears for the consonant-word recognition. (This was also true of the Thai subjects). No significant difference by this scoring was found for either group (untrained or trained) on either the tones or the hums. This is in contrast with the Thai subjects, who showed a significant right ear effect on the tone-words (but not on the hums).

Figure 3 summarizes the results of the three groups, musically untrained (u), trained (t), and Thais (T). The percentage of error scores for the left ear (right ear advantage) are nearly identical in the untrained and trained English speakers in each task (49%). In the tone-word task, both groups of English speakers perform differently from Thai speakers. In the consonant-words task, all three groups show a right ear advantage, and no significant difference between the groups is found. In the hums task, all three groups show no significant ear advantage. These significance level differences are displayed in Table 4.

A comparison of subjects’ performance across stimulus-conditions, for the three groups (untrained, trained and Thai) is shown in Table 5. Both Wilcoxon and Spearman’s $\rho$ analyses yielded consistent results on the three groups’ performance across tasks. There was no difference in the non-Thai speakers’ (both trained and untrained) performance on tones compared to hums, but the Thai group differed significantly in their scores between these two conditions. Only the Thais did not differ in processing the tone-words as compared with the consonant-words; and all three groups differed significantly ($p < .01$) in their performance on consonant-words and hums respectively.

These results indicate that this most linguistic function of pitch discriminations in language, the use of pitch for phonological distinctions in a tone language, is lateralized to the left hemisphere.

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Furthermore, the results strongly support the functional interpretation of dichotic listening results, in that stimuli structured into linguistic units are processed in the left hemisphere, whereas similar or identical stimuli not so structured are not lateralized to the left hemisphere. The studies reviewed above have described right or left ear effects for pitch in the linguistic signal with a left ear advantage more often for less structurally linguistic pitch cues, such as sentence contour, emotional tone, and hums. An overview of the evidence suggests that points on a scale of pitch function correspond to lateralization of pitch processing in the brain. The findings in the Thai study, when considered with other dichotic listening findings, are compatible with the notion that pitch discriminations in language comprise a functional scale of most linguistically structured to least linguistically structured, and that points along this scale are associated with lateralization of processing.

SUMMARY

Pitch phenomena in the acoustic signal serve various functions which can be arranged along a hypothetical scale, according to a parameter called degree of structure or systematization (See Figure 1). On this scale, the most highly structured (or systematic) kind of pitch pattern, phonological tone, falls at one end of the scale, while emotional and personal patterning of pitch phenomena are at the other end of the scale. Intermediate functions are found in word-stress and phrasal contour. Pitch cues in music can be represented in a similar way; studies similarly show that melodies tend to be processed preferentially by the left hemisphere, particularly by musicians, who presumably have engaged an analytic mode for the task. Harmonic information, forming a complex pitch pattern, is specialized in the right hemisphere, according to several studies. This predicts that recognition of familiar orchestral textures would be specialized in the right hemisphere.
Table 4. Significance levels for ear difference in musically untrained (u), musically trained (t) and Thai groups (T) on the three dichotic listening tasks.

<table>
<thead>
<tr>
<th></th>
<th>tones</th>
<th>CVs</th>
<th>hums</th>
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<tbody>
<tr>
<td>u</td>
<td>NS</td>
<td>p&lt;.05</td>
<td>NS</td>
</tr>
<tr>
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<td>NS</td>
</tr>
<tr>
<td>T</td>
<td>p&lt;.01</td>
<td>p&lt;.01</td>
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Table 5. Significance levels for stimulus-conditions compared by performing Wilcoxon and Spearman's analyses on left ear Percentage of Errors scores from same-subject pairs.

<table>
<thead>
<tr>
<th></th>
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</tbody>
</table>
The data gathered together in this monograph show a consistent picture of hemispheric specialization with respect to pitch processing in the linguistic signal. Left hemisphere specialization is associated with highly structured pitch contrasts, such as phonetic voicing cues and tones (shown in dichotic listening studies). Aphasia studies, too, suggest that tonal abilities are impaired in left hemisphere damage in tone-language speakers. Right hemisphere specialization is overwhelmingly the case for pattern of pitch functions in speech that are least structured, those cueing emotional and personal information. Specifically, various dichotic listening and clinical studies show that the right hemisphere is specialized for emotional tone and voice quality. The view schematized in Figure 1 predicts that word-level pitch contrasts would be impaired in aphasics. The study of English word-level contrasts, which demonstrated aphasics' abilities in recognizing these words, does not actually constitute clear counterevidence, because word-stress contrasts make up a small and fluctuating portion of English grammar. In other words, lexical pitch contrasts in English are not highly systematized. It is likely that tests of word-level pitch/stress contrasts in Swedish, or Japanese would reveal an impairment in aphasics and a right ear effect in dichotic listening in normals, because such contrasts are productive—and more highly structured—in those languages. Studies of the syntactic use of pitch contours (intonation) have yielded equivocal laterality results. This is reflected in Figure 1 by the place of the syntactic function of pitch, lying midway between the structural units of tone and the unstructured patterns of voice quality. The ambiguous status also appears in linguistic descriptions of intonational contours (described in the beginning of this article), which tend to characterize intonation as both gradient and discrete. These observations are in keeping with the notion that the speech signal is heterogeneously processed; different components of the signal are processed in different parts of the brain (Van Lancker, 1973). The conclusions drawn in this paper about the functional differentiation of pitch processing in the cerebral hemispheres fit current assumptions about the hemispheric modes of processing, wherein the left hemisphere is specialized for analytic and/or sequential tasks, and the right for synthetic and/or pattern recognition tasks (Levy, 1977; Zaidel, 1977).

Figure 3. Percentage of errors (made at the left ear) for musically untrained (u) musically trained (t) and Thai groups (T) on the three dichotic listening tasks.
The lack of a REA for Cantonese tones (Benson et al., 1972; Smith and Shand, 1974) and Yoruba tones (Curtiss and Lord, 1974) prepared for dichotic listening was probably due to the high accuracies obtained in the experimental designs.

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