TONE PROCESSING AND THE BRAIN

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One of the most intricate changes that occurred during the evolution of modern man is the development of highly sophisticated and differentiated language systems. Since the necessary hardware for processing language resides in the brain, evolution of the human brain and the development of language systems have gone hand in hand. Biologically, these two factors represent the most striking features distinguishing human beings from subhuman species.

A particularly challenging area of interest concerns the study of how language is processed by its user, including both the input side of comprehension of written or spoken speech, and the generation and production of linguistic output.
Partly due to the complexity and speed of ongoing processing, direct observation of the separate steps involved has proved extremely difficult. Thus, even within the behavioral sciences, most research has centered on indirect analyses of outcomes (i.e., products of processing), seeking to draw inferences about how linguistic processors might be organized in the brain in order to explain the observed results.
A somewhat different approach aims to relate individual linguistic or other cognitive functions to more or less circumscribed areas of the brain. Starting way back in the early 19th century, one method used in investigating such structure-function (i.e., brain-behavior) relations represented the systematic observation of the effects of brain lesions with different localization. Since then, a wide body of evidence has been collected on neurological and cognitive deficit correlates of open- or closed-head injuries. However, given the extreme complexity of the affected organ, the large variability in nature and extent of the individual damage, the high redundance present in brain circuitry, and the resulting potential strength of compensating mechanisms, this method provides somewhat vague information on how and where specific cognitive functions are localized in the healthy brain.

Nevertheless, one pattern that emerged very clearly concerned the dominant role of the left cerebral hemisphere (and, in particular, the left temporal regions) for language comprehension and production. Thus, it has long been established that the most complex and exclusively human cognitive abilities are lateralized, i.e., chiefly represented in one half of the cortex, in contrast to symmetrically organized elementary perceptual and motor functions.

Seeking to overcome the limited conclusiveness of lesion studies, a number of behavioral paradigms have been developed to determine which of the two sides of the brain is more strongly involved during the execution of a variety of cognitive tasks presented to normal subjects. Due to the preponderance of crossed neural pathways linking each perceptual hemispace with brain structures, differences in performance following presentation of stimuli on the left vs. right side reflect the use of lateralized cerebral functions and, thus, are regarded as evidence of lateralization of highly specialized processing activities.
In the visual modality, asymmetrical cerebral functions can be assessed by comparing performance measures following tachistoscopic presentation of stimuli in the right vs. left visual field. On the other hand, auditory processes have frequently been studied with the dichotic listening paradigm (Figure 1).
As shown in the illustration, monaural stimuli have

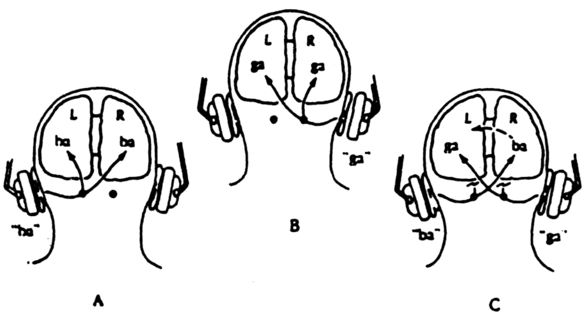

Figure 1: Access of auditory stimuli to the two cerebral hemispheres in (A) left or (B) right monaural, and (C) dichotic listening conditions (Springer & Deutsch, 1981)

direct access to both hemispheres by either ipsi- or contralateral pathways. In dichotic presentation, the efficiency of the weaker uncrossed pathways is suppressed, stimulus traces are propagated to the contralateral hemisphere. Linguistic stimuli presented to the left ear are channeled to the right hemisphere and then have to cross the corpus callosum in order to reach the left hemisphere specialized for linguistic processing. This extra step requires additional time and is associated with qualitative degradation, resulting in poorer identification performance. While representing a powerful tool for investigating cerebral lateralization of function in healthy subjects, great care must be taken in the preparation of dichotic stimulus material. One important requirement concerns the perfect temporal overlap between the two stimuli presented simultaneously. Other points include equivalence of amplitude and duration of the stimuli, as well as the perfect alignment of the two tracks of the dichotic stimulus tape (Porter & Hughes 1983). When adequate precautions are taken, the right-ear advantage (REA) found for linguistic stimuli represents a behavioral correlate of language processes lateralized to the left hemisphere. The magnitude of the REA for linguistic stimuli even appears to be associated with psychometric measures of verbal abilities, while left-ear advantage (LEA) for recognizing six-tone melodies in a musical task seems more strongly related to spatial abilities (Bryden 1986).
Visual half-field and dichotic stimulation studies both confirmed and further elaborated earlier notions that handedness is an important factor determining cerebral organization (i.e., direction and extent of lateralization of cerebral functions). As demonstrated by the large inter- and intraindividual variability in performance asymmetries, these methods have also shown that functional cerebral lateralization is not an all-or-none phenomenon, but is rather expressed as a relative preponderance of activity and/or superiority of performance of one hemisphere as compared to the other half-cortex while a person is solving a given task by using a particular strategy. Hence, observed asymmetries in performance may be influenced to varying degrees by stimulus and task properties, context, experience, practice, strategy, and other factors.

Mecacci (1981) considers the comparison of the degree of hemisphere specialization in different populations to be a highly promising line of investigation in the area of cross-cultural neuropsychology. By comparing information-processing phenomena and/or cerebral organization patterns among different cultures, one will eventually gain increasing knowledge about both cognitive processes (including linguistic ones) and the brain (Fabrega 1977).

The different language systems that evolved make use of varying dimensions and properties of the acoustical signal. While most Western languages utilize the same physical dimensions and draw their basic elements from very similar sets of phonemes, tone languages are unique in using levels and changes of pitch as phonemic attributes with highly salient semantic function (cf. Gandour 1978 for a review of tone languages). On a scale of levels of functional pitch in the speech signal, languages such as Chinese or Thai with their phonological tones on single segments or syllables would be placed at the "most systematically linguistic" end (Van Lancker 1980).

Obviously, linguistic and external context provide additional information in connected speech. In contrast, isolated presentation of otherwise identical monosyllabic (CV or CVC) tone words in a neutral setting creates a situation where a person must entirely rely on the tonal dimension in order to identify each stimulus. In speakers of a tone language, the distinction between different tonal patterns is thus one aspect of their language comprehension abilities. Hence, tone discrimination and identification tasks can be expected to activate those brain structures that are responsible for language processing (i.e., the left cerebral hemisphere), since this is where decoding and comprehension of the utterance takes place.

Several studies on tone production and comprehension in brain-injured tone language speakers were able to demonstrate such left-hemisphere processing of tone words (Gandour & Dardarananda 1983, Packard 1986, Gandour et al. 1988). However, perceptual studies using genuine words of a tone language as stimuli could always be expected to elicit a left-hemisphere advantage (=REA) in subjects with sufficient knowledge of the language, i.e., who "understand" the presented words and can link them to lexical elements. On the other hand, the same stimuli would represent meaningless sounds to persons who do not know the language.

In order to investigate the locus of processing of the tonal dimension (i.e., the tonal pattern itself), it is necessary to use otherwise non-linguistic, neutral tokens rather than words, thus presenting meaningless stimuli to all listeners studied. The tonal pattern superimposed on such synthetic sounds will constitute a

linguistic feature only for those subjects who are familiar with the tone language.
While most dichotic research on acoustic and phonetic feature effects has examined native speakers of English or other Western languages (cf. the comprehensive review by Tartter 1988), studies with speakers of a tone language are scarce, particularly those using semantically meaningless tone stimuli with linguistically relevant pitch contours. The only application of a dichotic listening paradigm with tone words and corresponding meaningless tonal stimuli (hums) found a REA (i.e., left hemisphere specialization) for tone only when real tone words were presented to Thai subjects, while hums failed to yield significant ear effects (Van Lancker & Fromkin 1973, 1978).
It is unfortunate that this line of cross-cultural research on normal subjects has not been followed up further, since a number of methodological problems may have affected these earlier results. Differing stimulus durations both within and between sets, use of linguistic symbols on answer sheets, failure to counterbalance order of stimulus sets, possible memory effects caused by instructions to recall both stimuli of each dichotic pair perceived, and questionable equivalence of tonal contours of the delivered real words and hums, in conjunction with the small number of (possibly not very representative) Thai subjects, cast a shadow of doubt on the general validity of the observed symmetrical identification of meaningless tone stimuli.

In an attempt to replicate Van Lancker & Fromkin's findings while avoiding the mentioned shortcomings, and aiming to gain further information on culture-specific processes underlying tone perception, a tone identification study was recently conducted with two groups of Thai and German nationals.

Subjects. Participants included 57 Thai undergraduate students at Chulalongkorn University (Bangkok) and 54 German undergraduates (University of Mannheim).

Stimuli. Natural-speech /Khaa/ stimuli bearing the five tones of standard Thai (originally used by Gandour & Dardarananda, 1983) were digitized (20 kHz sampling rate) and manipulated to generate a set of five linguistic /Khaa/ stimuli with identical duration and mean intensity, but retaining the fundamental frequency contours of the original natural-speech items.
A digital sound generator was used to superimpose the same fundamental frequency patterns on artificial square-wave signals, yielding the set of five non-

speech (i.e, meaningless) stimuli referred to as "neutral". With the aid of an Atari STF computer and MIDI software, balanced sequences of these individual stimulus elements were then aligned on the two tracks of a stereo cassette tape, with either the same tone (binaural sections), or two different tones (dichotic sections) being recorded on the two channels. Stimulus tapes were played on a stereo tape recorder (Philips D6920) and presented to subjects over headphones (beyerdynamic DT770).

Procedure. To avoid contamination of results by sequential effects, order of presenting the two stimulus sets was reversed for half of the subjects in each sample. Testing sessions were run with groups of three participants, who were asked to listen to the stimulus tapes and identify each perceived tone by circling one of five symbols representing the falling, low, mid, high, and rising tones. As the present study attempted to avoid any linguistic cues in task setting, neutral symbols (see Figure 2) were designed and presented to the subjects on answer sheets.

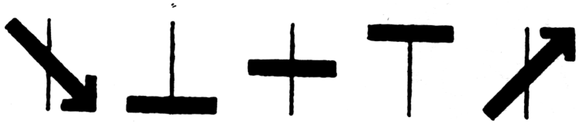

Figure 2 : Symbols used in answer sheets to mark falling, low, mid, high, and rising tones.

Binaural results. In order to assess general characteristics of the two sets of stimuli, error rates for each tone and frequencies of confusions between each pair of tones were calculated. Patterns of errors observed in Thai and German subjects for linguistic and neutral tonal stimuli are shown in Figure 3. For illustrative purposes, results are reported as diagrams, rather than in the original confusion matrices from which they derive. While the direction of the observed confusions is neglected in this form of presentation, the full pattern of errors is visualized more easily, facilitating comparisons between groups and stimulus types. In Figure 3, size of circles indicates the percentage of overall identification errors for a particular tone (i.e., 25 % = 75 % correct identifications). Thickness of connecting lines illustrates the relative frequency of confusions between pairs of tones, combined across the two possible directions. These percentages of confusion add up to the total error rate (i.e., 100 % minus total percentage of correct identifications in each condition).

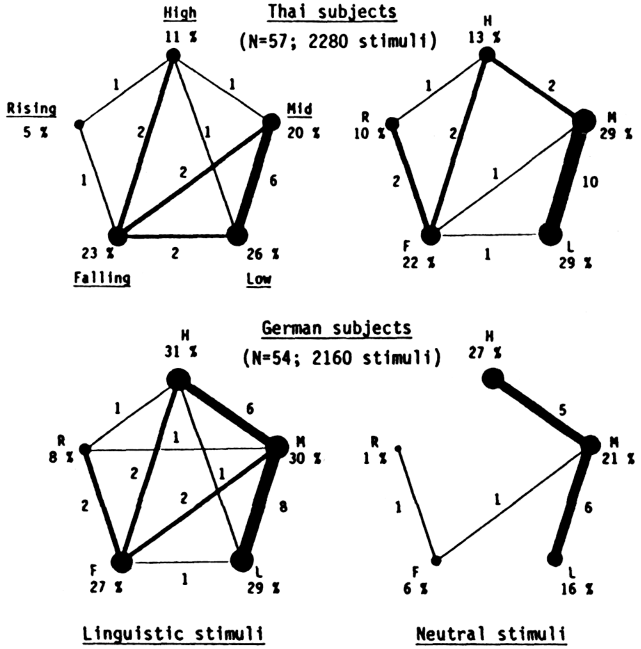

Figure 3 : Analysis of errors made during binaural presentation of tone stimuli.

In the Thai group, linguistic and neutral stimuli led to very similar error patterns. Irrespective of the type of stimulus carrying the presented tonal contours, Thai subjects showed highest confusion rates between the mid and low tones. These two, along with the falling tone, were misidentified most often, while the highest rate of correct responses occurred for the rising-tone stimuli. For Thai subjects, presentation of real Thai words slightly improved overall performance, as compared to neutral stimuli.
In addition to the mid/low confusions, German listeners also had problems identifying the high tone. Interestingly, neutral siren-like stimuli improved overall per-

formance in the German group, particularly with respect to the dynamic tones with falling and rising contours.

Dichotic results. In alternating sections, the same stimuli were also presented dichotically (i.e., simultaneous presentation of one tone on the left and a different one on the right side), with subjects receiving the instruction to report only the tone heard on the indicated side. After 10 dichotic pairs, the attended side was changed. Thus, comparisons between error rates for right-ear and left-ear stimuli indicate the relative contribution of the two cerebral hemispheres in the dichotic tone identification tasks. Apart from the total left- and right-sided errors that occurred, a further measure of interest concerned the so-called intrusion errors (i.e., subject's response coincides with the tone presented on the opposite side). Asymmetries of such errors of intrusion are generally regarded as additional evidence of the bias or strength of preference for reporting stimuli presented to the opposite ear, inspite of the explicit instructions to disregard these simultaneous distractors on the unattended side.
Before such interpretations can be inferred, it is necessary to exclude data of subjects with general asymmetries in hearing thresholds and left-handed and ambidextrous subjects, since only right-handers represent a homogeneous sample with respect to cerebral lateralization of language functions.
Dichotic tone identification data of the remaining samples of right-handed subjects with symmetrical hearing thresholds (45 Thai subjects and 44 Germans) were analyzed with repeated-measures analyses of variance, with attended ear and stimulus type representing the within-subjects factors, while overall error rates as well as percentage of intrusion errors served as dependent performance measures. In addition to separate (2 x 2) analyses within the two groups of subjects, a combined 3-way analysis of variance was carried out, which included the additional betwen-subjects factor of nationality. Table 1 shows the results of the three repeated-measures ANOVAs for total error and intrusion error rates illustrated in Figure 4. Length of the bars in Figure 4 symbolizes the relative contribution of the ipsilateral hemisphere for producing correct responses (i.e., more errors in attend-left condition = better right-ear performance signifying left-hemisphere advantage for processing the stimuli). Simple effects for adjacent bars were compared with two-tailed Wilcoxon tests (see Table 1 for results of full analyses of variance).

Table 1: Repeated-measures analyses of variance for the German and Thai groups, and for the combined sample including between-subjects factor of nationality

a) Total errors

Source	German	Thai	Both groups combined: Main effects	Both groups combined: x group
Group (D,T)	-	-	-	***
Side (L,R)	ns	T	ns	*
Stimulus type	ns	***	**	***
Side x Stimulus	ns	ns	ns	ns

b) Intrusion errors

Source	German	Thai	Both groups combined: Main effects	Both groups combined: x group
Group (D,T)	-	-	-	*
Side (L,R)	T	*	ns	**
Stimulus type	ns	**	**	T
Side x Stimulus	ns	T	ns	ns

*** $p \leq .001$; ** $p \leq .01$; * $p \leq .05$; T: $p \leq .10$.

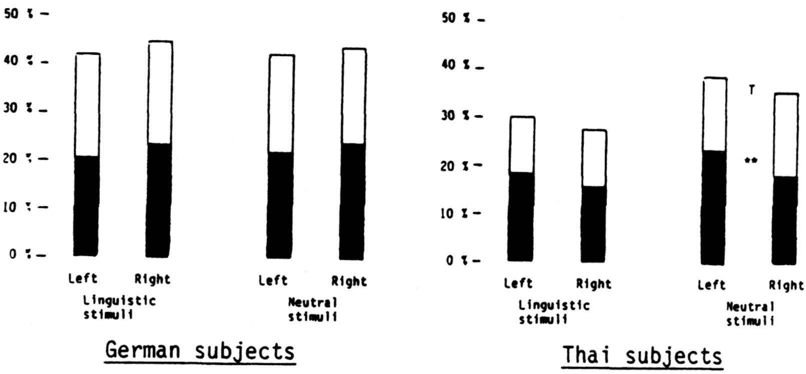

Figure 4 : Dichotic results for tonal patterns on linguistic /Khaa/ stimuli and neutral tones in attend-left and attend-right conditions: Mean percentages of total errors (full length of white bars) and intrusion errors (black portion of bars)
** $p \leq .01$; T: $p \leq .10$

In the German group, slightly enhanced error rates for linguistic and neutral stimuli heard through the right channel represent a nonsignificant overall LEA in both sections of the dichotic task. Stimulus type did not affect performance in these subjects unfamiliar with linguistic tone processing (cf. Table 1 and Figure 4). In contrast, Thai listeners made fewer errors when responding to right-ear stimuli. This pattern was obtained for both linguistic and neutral tone stimuli alike. In fact, substantial ear effects only occurred when Thai subjects listened to meaningless neutral tones, which yielded higher rates of total errors ($p \leq .10$) and intrusion errors ($p \leq .01$) for left-ear stimuli. Overall, Thai listeners made significantly fewer errors when identifying real tone words of their own language, compared to when neutral tones were presented.
The superior performance of Thai subjects when identifying real words could still be demonstrated in a combined analysis of data from the two groups, where the factor of stimulus type represented the only significant within-subjects main effect. Compared with the German sample, Thai listeners produced significantly fewer overall misidentifications and intrusion errors. Apart from the mentioned impact of stimulus type on the Asian subjects' performance, analysis of the combined data sets revealed a significant group-by-side interaction: Contrary to the German group, higher error rates in the Thai sample were more frequently associated with left-ear than with right-ear stimuli. Occurring for both performance measures (total errors: $p \leq .05$; intrusions: $p \leq .01$), this effect demonstrates generally different patterns of performance asymmetries and reflects differential use of cerebral resources in speakers and nonspeakers of the Thai language. Inspection of mean error rates in Figure 4 and the lack of a three-way group-by-side-by-stimulus interaction show that these differences in lateralization were equally observed for both linguistic and neutral tone stimuli.

Discussion. In the binaural condition, analysis of error patterns observed in Thai subjects reveal little evidence of differential processing of tonal contours carried by linguistic vs. neutral meaningless stimuli. The reported pattern of errors (i.e., the relative abundance of mid/low confusions) closely resembles those found in other studies using natural-speech stimuli presented to normal Thai subjects (Abramson 1976, Gandour et al. 1988), suggesting that the manipulations performed to equalize duration and average intensity of these stimuli had little impact on their usefulness as valid tokens representing the five Thai tones.

Compared with confusion matrices reported in earlier studies, overall performance level was found to be much lower in the present investigation, and included a general scatter of different errors of confusion. This discrepancy may be attributed to higher task demands in connection with a faster presentation rate, as well as the intentional use of unfamiliar symbols on subjects' answer sheets.
German subjects demonstrated similar error patterns as the Thai group, but proved less accurate at identifying the high tone. The most obvious differences between the two samples concerned the relative performance in the linguistic vs. neutral-tone conditions: While Thai subjects benefited from having genuine Thai words carry the tones, the opposite was true in the German group, who showed a much higher rate of correct identifications for artificial siren-like stimuli.
Thus, descriptive analyses of the binaural sections of the reported study and comparisons between groups and types of stimulus provide an initial clue suggesting that the processing of tonal patterns is organized differently in speakers vs. nonspeakers of a tone language. On the other hand, the close resemblance of the two error patterns observed in the Thai sample may be taken to indicate that, in tone language speakers, tone identification processes are not affected by the presence or absence of other linguistic features. In other words, identification of isolated tonal features seems to occur in a similar manner as when the tones are carried by real words.

Turning to the dichotic results, Thai listeners showed identical performance asymmetries to both types of stimuli presented. Contrary to the German group, right-ear (left-hemisphere) advantage for both linguistic and meaningless tones was observed for these subjects accustomed to using tones as phonemic features.
Comparison with previous dichotic listening results (Van Lancker & Fromkin 1973, 1978) suggests that, in their study, higher-level lexical processing was associated with the observed REA for real tone-words, rather than phonemic (or "tonemic") decoding of pitch contours which were also present in the otherwise nonlinguistic hum stimuli. However, absence of right-ear superiority for meaningless tones would seem to imply that the activation of left-hemisphere tone pattern processors would have to be preceded by a (top-down) evaluation of whether or not the perceived stimulus is of a linguistic nature. Thus, only linguistic stimuli (i.e., real words) would be channeled to left-hemisphere tone analyzers for further lateralized proces-

sing. Stimuli identified as meaningless would not gain access to these specialized left-hemisphere processors. Even when the subject is aware of the nature of the task and recognizes the similarity between the presented stimuli and the familiar tonal patterns of his native tone language, he fails to utilize highly specialized cerebral resources, although these would be particularly useful during the task.

In view of the present findings, this questionable interpretation is challenged by evidence in favor of a general lateralization of tone identification processes in tone language speakers (i.e., left-hemisphere tone processing irrespective of the nature of the stimuli carrying the tonal contrasts). Since tonal features in tone languages seem linguistically equivalent to consonant features, this conclusion seems well in line with the notion that "left-hemisphere specialization was found for sounds only when they were part of a linguistic system in the perceiver" (Van Lancker & Fromkin 1978, p.22).

Outlook. Recently, various dichotic listening investigations have been conducted with musical stimuli of differing complexity (e.g., Burton et al. 1989), finding inconsistent results depending on the particular musical aspect, task difficulty, musical experience, and processing mode employed during the task.
In a dichotic listening study using linguistic and nonlinguistic stimuli (including single or triple musical tones) presented to Canadian and Chinese subjects, Cohen et al. (1989) failed to find a REA for the tone tasks in Chinese subjects. Both groups demonstrated a LEA (i.e., right hemisphere superiority) for complex triple tones. However, it should be noted that the tones used in this study were musical stimuli which did not resemble those occurring in the Chinese language.
Minagawa et al. (1987), on the other hand, reported REA for recognizing six-note melody sequences of pure tones in a group of musicians, while nonmusicians initially showed a LEA which later reversed to a REA in a second testing session. Thus, dichotic ear advantages may change over time, presumably reflecting changes in processing strategies as subjects become more familiar with the task.
If not only stimulus properties, but also subjects' experience can affect behavioral indicators of cerebral organization, then it seems likely that performance asymmetries are behavioral expressions of lateralized cerebral information-processing functions associated with previous experience, whereas the actual strategy

utilized while performing a given task determines which of a number of possible alternate functions will be activated. Hence, explicit instructions to follow either a typical left-hemisphere (linguistic/analytical) or a characteristical right-hemisphere (spatial imagery) strategy might be expected to have an influence on the direction and degree of performance asymmetries.
Using the same tone stimuli as described, this issue was taken up in a follow-up study with two groups of German subjects, who listened to (in their case, meaningless) /Khaa/ tone words both before and after receiving instructions to use either a linguistical or a spatial imagery strategy to facilitate identification of the dichotic stimuli. At the end of the session, participants were asked whether their application of the respective strategy had made the task easier or more difficult. Results showed that the general non-significant left-ear (right-hemisphere) effect reversed to a REA only in a subgroup of subjects who reported facilitation of the task through the use of a linguistical strategy.
This finding further supports the notion that observed patterns of dichotic listening asymmetries may not only appear to reflect different cerebral organization in tone language speakers vs. nonspeakers due to the different quality of their previous (linguistic) experience, but can also indicate the employment of different processing strategies employed during the tone identification task.

Obviously, more systematic research is necessary to fully understand cerebral tone processing. If instructions to use a specific strategy are able to produce a left-hemisphere shift in subjects unfamiliar with linguistic tones, one may suspect that variation of certain stimulus properties (e.g., their meaningfulness) may do the same. In a further study presently in preparation, German subjects will again hear tonal stimuli as described above, but with tonal contours superimposed on /Jaa/ rather than (meaningless) /Khaa/ syllables. Since "Ja" (=Yes) is a German word often used as one-word sentence with varying intonation (e.g., "Ja?", "Ja!", "Ja...") bearing different meanings, analysis of ear asymmetries for this particular stimulus can be expected to yield interesting results.
Minor modifications of the dichotic listening paradigm would allow to apply this method in a number of further areas, including studies on the development of functional asymmetries for tone processing during either first- or second-language acquisition, or cross-cul-

tural comparisons between speakers of different tone languages.
Another interesting option is the combination of similar dichotic tasks with neurophysiological methods. Correlates of the reported functional asymmetries can well be expected to show up in event-related potentials extracted from simultaneous multi-channel EEG recordings. Thus, converging evidence on functional laterality effects during tone processing would be gained by comparing asymmetries in performance measures and task-related electrical activity recorded from different locations over the brain. Future applications of even more complex methods measuring regional cerebral blood flow, oxygen consumption, or local glucose metabolism rates (Mazziotta et al. 1982) during the administration of tone identification tasks may eventually yield further insight into the underlying cerebral processes.

Conclusion. According to Luria (1973, pp.133-134) phonemes as the sounds of speech are organized into a particular sequence which depends on the phonemic system of a given language. In order to distinguish between them they have to be coded by picking out the useful, phonemic (or meaning-distinguishing) features and separating them from features which play no part in the differentiation of word meaning. Features found in some languages do not exist in others. Since the temporal cortex of the left hemisphere is specially adapted for the analysis and synthesis of these sounds of speech and, hence, for qualified speech hearing, left-hemispheric superiority may be expected to include all salient features of a language.
One of the authors of earlier reports on dichotic tone effects in Thai subjects concludes that "hums yielded no significant ear effects because they were not linguistically structured (although containing the same contrasts as the tones)" (Van Lancker 1980, p.235). However, observations on Chinese aphasics have been interpreted as "neurolinguistic evidence that tones in Chinese are 'phonemes' in the same sense as consonants" (Packard 1986, p.220). Since consonants do not need to be coupled with semantic content in order to elicit a right-ear advantage, the same can be expected to hold true for tonal contours.
The results of the present study disagree with the previous finding in that they demonstrate asymmetrical phonemic processing of tonal features even in the absence of other concurrent linguistic or semantic cues. They suggest that, in native speakers of a tone language, cerebral lateralization of cognitive functions is already present at an early level of auditory pro-

cessing, irrespective of other linguistic features that might grant the perceived stimuli access to higher-level semantic processing. They also indicate that analysis of a particular physical dimension of the acoustical signal may or may not be lateralized, depending on the set of phonemic features a person has learned to distinguish during the acquisition of his particular language system.

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