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REVIEW

Hemispheric specialization of linguistic pitch patterns

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[Received 2 January 2002; Revised 1 July 2002; Accepted 7 July 2002]

ABSTRACT: Pitch is used to signal different aspects of language such as speaker identity, intonation, emphatic stress, and word identity (as signaled by lexical tones). This article reviews research studies investigating hemispheric specialization of these pitch patterns in the context of two competing hypotheses. The functional hypothesis states that pitch patterns are lateralized to different hemispheres of the brain depending on their functions. Those pitch patterns that carry a greater linguistic load (e.g., lexical tones) are lateralized to the left hemisphere, while those that carry a less linguistic load (e.g., intonation patterns signaling affective moods) are lateralized to the right hemisphere. The alternative hypothesis, the acoustic hypothesis, states that all pitch patterns, regardless of their functions, are lateralized to one hemisphere (the right hemisphere in particular). Although most researchers support the functional hypothesis, a comprehensive review, which includes lesion, dichotic-listening, and functional imaging studies of different types of pitch patterns, does not support this view. Moreover, little evidence exists for the alternative hypothesis. Possible methodological problems of these studies, alternative hypotheses, and considerations for future research are noted. © 2002 Elsevier Science Inc. All rights reserved.

KEY WORDS: Prosody, Brain lateralization, Neurolinguistics, Aphasia.

INTRODUCTION

This review focuses on the functional asymmetry of the two human cerebral hemispheres, and more specifically, on the notions of left hemispheric dominance for language-related behaviors and right hemispheric dominance for pitch-related behaviors. The primary focus will be on pitch patterns that are used in language.

Although no explicit correlation was made, observations of the co-occurrence of speech disorders and left hemisphere deficits were reported even as far back as Hippocrates' time (born 460 B.C.) [1]. Among the first to suggest that discrete brain areas correlate with linguistic behaviors were Gall and Bouillaud, who published numerous cases showing the link between lesions in specific areas of the brain and the loss of specific language (and other) functions [2]. This localization view was further confirmed by Broca and Wernicke, who explicitly proposed that language is lateralized to the left hemisphere with lesion to the posterior part of the frontal

lobe leading to nonfluent aphasia¹ "aphemia" [3] and lesion to the posterior part of the first temporal gyrus leading to fluent/sensory aphasia [4].

This anatomic-localization view of aphasia was later challenged by followers of the more holistic "cognitive school" of aphasia, who believed that language is not separate from general cognitive functioning. In other words, the apparently motoric, sensory, and other aspects of language cannot be distinctly dominated by discrete brain areas for they do not exist on their own. Trousseau, Jackson, Head, Marie, and many others reported cases in which aphasic patients, whose deficits appeared to be only linguistic in nature, were in fact experiencing more than language deficits [5]. They argued that aphasic symptoms are the verbal forms of broader cognitive deficits. For example, aphasic patients, who have object naming and word finding problems, would also be expected to have problems with nonverbal tasks such as object classification and color sorting. They believed that these patients had a problem with abstract reasoning which could be seen in both verbal and nonverbal forms, if they are tested carefully.

The work of Geschwind [6,7] signaled a revival of the localization school. He explained the linguistic and psychological impairments of aphasia by lesions to discrete cortical areas, lesions to fibers connecting different cortical areas, or both. Although scientists from the localization and cognitive schools disagree on several key issues, they both agreed that language is closely tied to the left hemisphere.

While the lesion approach had been dominant since the time of Hippocrates, several experimental strategies in addition to the lesion approach have been used to investigate the neuroanatomical correlates of language. Using a dichotic-listening technique, for example, Berlin et al. [8] and Zurif and Sait [9] found a right-ear advantage (REA) for the perception of consonant–vowel nonsense syllables and English sentences, thus demonstrating a left hemispheric dominance for language processing. More recently, Ip and Hoosain [10] found similar results, when Chinese listeners were presented Chinese words dichotically.

Using functional neuroimaging techniques, various studies have demonstrated that the left hemisphere is dominant for linguistic behaviors. For example, by using positron emission tomography (PET), Zatorre et al. [11] found that listeners had increased brain activations, as demonstrated by regional cerebral blood flow (rCBF) in various parts of the left hemisphere, when actively discriminated

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final consonants of syllables relative to when listened passively to the same stimuli.

The right hemisphere has been viewed as specialized for pitch-related behaviors. A number of research studies have provided evidence for this view. For examples, Robin et al. [12] found that right hemisphere-damaged (RHD) patients performed significantly worse than left hemisphere-damaged (LHD) patients and normal subjects in discriminating pitch differences. Peretz [13] similarly found that RHD patients had problems identifying rhythm-neutralized melodic (pitch) contours compared to LHD patients and normal subjects. In a dichotic-listening study, Cohen et al. [14] found a left-ear advantage (LEA) for melody perception, indicating right hemispheric dominance for pitch-related processing. In a PET study, Zatorre et al. [15] found that, when compared to the condition in which listeners passively listened to English speech stimuli, an increase of rCBF in the right hemisphere was observed when listeners were required to discriminate pitch contours of the same stimuli. Similarly, relative to listening to an acoustically matched noise sequence, an increase of rCBF was observed in the right hemisphere when subjects listened to melodies or made pitch judgments of the first two notes of a melody [16].

PITCH PATTERNS USED IN LANGUAGE

The section above briefly described several studies that demonstrate left hemispheric dominance for linguistic behaviors that do not involve pitch, and right hemispheric dominance for pitch-related behaviors that do not involve language. It is interesting to consider pitch contours that are used in language. Pitch is used to signal several aspects of spoken language. It can be used to distinguish affective moods (e.g., higher pitch, when the speaker is happy), to distinguish a question from a statement (e.g., “This is good” vs. “This is good?”), to distinguish phonemic stress patterns used in noun phrases and compound nouns (e.g., *blackboard* vs. *black board*), to distinguish contrastive/emphatic stress patterns (e.g., This is *Tom’s* book, not *Mary’s*), and to distinguish lexical/phonemic tones such as in Mandarin Chinese (e.g., /ma/ in high pitch means “mother” whereas /ma/ in falling pitch means “to scold”).

Diverging theoretical implications follow depending on which hemisphere is dominant for pitch patterns used in language. Van Lancker [17] proposed a scale of hemispheric specialization associated with different domains of pitch contrast with lexical tone being the “most linguistically structured” and affect and voice quality being the “least linguistically structured.” When pitch contrasts are more linguistic, they are lateralized to the left hemisphere; on the other hand, when they are less linguistic, they are lateralized to the right. If Van Lancker is correct, it means that lateralization depends on the *function* of the physical/acoustic correlates of language (henceforth, the *functional account*). In other words, the brain recognizes the contexts in which physical cues are present. Alternative to the functional account is an account which states that the same physical cue is processed by the same areas of the brain regardless of the contexts in which it occurs. This account predicts that all pitch contrasts, lexical or nonlexical, are processed mainly by the right hemisphere, i.e., lateralization depends on *acoustic* properties independent of function (henceforth, the *acoustic account*). It is outside the scope of the current article to discuss the processing of temporal cues, but as will be discussed, the left hemisphere has been proposed to be specialized for temporal cues (e.g. [18]).

Interestingly, the two accounts of hemispheric specialization of pitch processing are related to the two schools of aphasiology discussed earlier. The acoustic account resembles the more holistic cognitive school, which focuses on viewing language as part of

the overall mental ability. The acoustic account views lexical tone processing to be within the scope of general pitch processing, and because pitch processing is lateralized to the right hemisphere, lexical tone processing must be lateralized to the right hemisphere as well. The functional account, on the other hand, resembles the localization school, which focuses on connecting language and its components with specific brain areas. Because language is believed to be separate from general cognitive functioning and components of language are localized in cortical areas of the left hemisphere, lexical tones, being part of language but outside general pitch processing, must be localized in a specific area in the left hemisphere similar to other language components.

Review articles covering the topic of hemispheric specialization and pitch processing exist in the literature; however, none of them provides a review as comprehensive as the current nor do they provide a detailed analysis of each study. As a result, conclusions drawn from these reviews are only reflections of some of the studies or they are largely based on the interpretations of the authors without considering in detail how the studies were conducted. In one review, Snow [19] argued that the right hemisphere is responsible for both affective and linguistic processing. However, this conclusion is based on a partial review of the literature. While Snow cited studies supporting his conclusion (e.g. [20,21]), many that are contradictive to his conclusion were not mentioned (e.g. [22–24]). Furthermore, few lexical tone studies, which are generally argued to be left-lateralized behavior, were discussed. Baum and Pell [25] also provided a review of the topic, but they presented a different conclusion. They concluded that pitch that is used contrastively at the word level is lateralized to the left hemisphere. At the sentence level, they concluded that the results are mixed although few would argue that the right hemisphere is not implicated in the processing of affective prosody. As will be discussed later in this article, a careful look at the studies of lexical tone and word-level stress would lead to the conclusion that little evidence exists for left hemisphere specialization. Furthermore, I will review studies that did not find right hemisphere specialization for affective prosody (e.g. [26]), as well as providing an analysis of why many studies which seemingly showed evidence for this conclusion are in fact problematic.

In the remainder of this article, I will review studies investigating hemispheric dominance for pitch patterns used in language. I will first review studies examining nontonal pitch patterns, specifically, affective prosody, nonaffective prosody at the sentence level, and phonemic and contrastive/emphatic stress patterns. Studies investigating lexical tones will be discussed in the last section. I will review studies primarily from three sources: lesion studies, dichotic-listening studies, and neuroimaging studies. Table 1 summarizes the lesion studies which comprise of the vast majority of the studies being reviewed.

NONTONAL PITCH PATTERNS USED IN LANGUAGE

Affective Prosody

In addition to other acoustic parameters used in speech prosody such as duration and loudness, pitch is used to signal different affective states (see [27] for a review). Using discriminant analysis, Pell and Baum [28,29] found that fundamental frequency (F_0), the physical correlate of pitch, is the only acoustic parameter that significantly distinguishes angry, sad, and happy speech. In this section, I will review studies investigating the role of the two hemispheres in the production and perception of affect in speech.

Production. Tucker et al. [30] investigated the effect of right hemisphere injury in affective speech. In their study, eight RHD patients and eight age-matched neurologically normal subjects

TABLE 1
 LESION STUDIES OF LINGUISTIC PITCH PATTERNS IN THE ORDER OF PRESENTATION IN THE TEXT

Study (Subjects)	Stimuli		Result Highlights
	Linguistic	Affective	
Production studies			
Tucker et al. [30] (8R; 8N) ^a		I	N > R
Shapiro and Danly [20] (5F; 11R; 5N)	P	P	R displayed different F_0 contours
Cancelliere and Kertesz [34] (18L; 28R; 20N)		I	Basal ganglia lesion the most predictive of aprosodia
Hird [31] (8R; 4N)		I	R had less F_0 variation
Baum and Pell [35] (4NF; 7R; 10N)	I	I	No general group difference but R had problem with F_0 contours
Pell [36] (10R; 10N)	I, F	I	R had less F_0 variation; N > R
Danly and Shapiro [51] (5NF; 5N)	I		Different F_0 contours
Danly et al. [23] (5F; 5N)	I		Different F_0 contours
Ryalls [24] (8NF; 11N)	I		Different F_0 contours
Seddoh [52] (15L; 16N)	I		N = L
Cooper et al. [53] (2NF; 3F; 4R; 5N)	I		L had timing and F_0 problems (no stats); R sometimes performed in between F and NF
Weintraub et al. [21] (9R; 10N)	I, F		N > R
Bryan [56] (30L; 30R; 30N)	I		N > L > R
Perkins et al. [57] (8L; 8R; 8N)	I		R = L
Behrens [54] (8R; 7N)	I		Different F_0 contours
Ryalls et al. [55] (19R; 9N)	I		R = N
Emmorey [60] (2F; 5NF; 6R; 12N) ^a	S		More R than L used F_0 to distinguish stress
Behrens [61] (8R; 7N)	S, F		R used fewer acoustic cues and judged to be less salient
Ouellette and Baum [62] (9NF; 8R; 9N)	S, F		R = NF = N in F_0 NF worst in timing
Packard [69] (8NF; 8N)	T, conson.		N > NF
Ryalls and Reinvang [70] (5NF; 5R; 1N)	T		N > R > NF
Gandour et al. [71] (4NF; 2F; 1R; 5N)	T		No large group difference, especially between R and L
Gandour et al. [72] (9F; 8NF; 11R; 20N)	T		N > F > R > NF
Gandour et al. [74] (9F; 6NF; 12R; 20N)	T, coartic.		No group difference
Gandour et al. [75] (9F; 5NF; 13R; 20N)	T, coartic.		N = R > F > NF
Bradvik et al. [26] (21R; 21N) ^a	I		N = R
Bradvik et al. [26] (20R; 18N) ^a	T, S		N > R in most tasks
Gandour et al. [78] (12R; 9N)	I		N > R
Ross et al. [79] (8R; 9N)	I		Different F_0 contours
Perception studies			
Tucker et al. [30] (7F; 11R) ^a		I	F > R
Heilman et al. [37] (6F; 6R)	Judge content of sentences	I	R = F (linguistic task; ceiling effect); F > R (affective task)
Heilman et al. [38] (5NF; 4F; 8R; 15N)	I (filtered)	I (filtered)	R = same errors in both tasks; L = more errors in the linguistic task
Blonder et al. [39] (6NF; 4F; 10R; 10N)	I	I	R worst in both tasks
Van Lancker and Sidtis [40] (24L; 13R; 37N)		I	N > R = L (but different error patterns)
Pell and Baum [28,29] (8NF; 2F; 9R; 10N)	I	I	N = R = L (affective task); N > L; R = L; R = N (linguistic task)
Pell [41] (6NF; 5F; 9R; 10N)		I	N > R = L (duration-neutral stimuli); N = R > L (pitch-neutral stimuli)
Weintraub et al. [21] (9R; 10N) ^a	I, S, F		N > R
Blumstein and Goodglass [63] (9F; 8NF; 13N)	S		N = L
Emmorey [60] (8NF; 7F; 7R; 22N) ^a	S		N = R > L
Baum [22] (8NF; 4F; 10R; 10N)	S, F		N > R = L (duration-neutral phonemic stimuli); N > L (contrastive stimuli)
Gandour and Dardarananda [66] (3NF; 1F; 1R; 1N)	T		R = N > L
Eng et al. [67] (5L; 5N)	T		N > L
Hughes et al. [68] (12R; 7N)	T	I	N = R (linguistic task); N > R (affective task)
Bradvik et al. [26] (21R; 21N) ^a	T, S	I	N = R
Bradvik et al. [77] (20R; 18N) ^a	T, S, F	I	N > R in most tasks

Subjects: N, neurologically normal; R, RHD; L, unspecified LHD; F, fluent aphasic (LHD); NF, nonfluent aphasic (LHD). Stimuli: T, lexical tone or pitch accent; I, sentence intonation; S, phonemic/lexical stress; F, contrastive/emphatic stress; P, paragraph; Conson., consonants; Coartic., coarticulation. Results: '=' , equal performance; '>', subjects could identify stimuli better than, or others identified subjects' production better than.

^a These studies have both perception and production portions.

were asked to repeat neutral sentences with specific emotional states (angry, happy, sad, or indifferent). Three judges listened to the subjects' speech and correctly identified affect in the normal subjects' speech significantly more often than in the RHD subjects' speech. The authors argued that the right hemisphere is specialized for the production of affect, which supports the functional account of hemispheric specialization. However, no LHD subjects were tested in this study because of their difficulty in performing repetition tasks. Without LHD subjects, it is difficult to determine whether the effect found was due to a general neurological deficit or a specific right hemisphere deficit. It is possible that an injury to the brain, no matter to which area, could impair the production of affect or even speech production in general. Furthermore, without the use of nonaffective stimuli that employ pitch (e.g., declarative sentences and questions), it is difficult to determine whether the results were due to a specific affective deficit or a general pitch control deficit. Hird [31] similarly asked RHD patients to produce sentences in different affective moods. Instead of asking listeners to identify subjects' intended emotions, Hird employed an acoustic analysis and found that relative to normal controls, RHD patients had less F_0 variation. Shapiro and Danly [20] added LHD patients as subjects and included stimuli that required the use of pitch to distinguish questions from declarative statements. By using acoustic analyses, they found that RHD patients, unlike the LHD and normal subjects, spoke with less pitch variation and restricted intonational range across *both* affective and nonaffective stimuli, supporting the acoustic account of hemispheric specialization.

Other studies that investigated the role of the cerebral hemispheres in the production of affective speech were conducted by Ross and coworkers. By using the Wada Test which involves intracarotid sodium amobarbital injections to one cerebral hemisphere to temporarily impair its functions, Ross et al. [32] found that, compared to their pre-Wada and post-Wada performance, subjects undergoing the Wada Test of the right hemisphere had difficulty signaling affect, with the control of F_0 being the most problematic. Ross et al. [32] argued that the right hemisphere is specialized for affective prosody. However, similar to Tucker et al. [30], no nonaffective stimuli were used. Ross [33] also reported a number of cases of RHD patients whom he classified as having a disorder he termed "aprosodia," a deficit in perceiving and producing prosody. Ross claimed that different types of aprosodia resulted from lesions in different regions of the right hemisphere. However, Ross' classification was based on the physicians' subjective bedside assessment. In a lesion study using standardized stimuli and objective assessment techniques, Cancelliere and Kertesz [34] did not replicate Ross' results. Cancelliere and Kertesz assessed 28 RHD, 18 LHD, and 20 normal control subjects on their ability to produce, repeat, and identify affective prosody based on the Battery of Emotional and Comprehension. Based on their performances, subjects were classified into categories of aprosodia. The results showed that six RHD and seven LHD were classified as global aprosodic; six RHD and three LHD were transcortical sensory aprosodic; five RHD were Wernicke's aprosodic; and three RHD and one LHD were Broca's aprosodic. In other words, lesions from either hemisphere could produce aprosodic syndromes. Furthermore, it was found that the basal ganglia is the most common lesioned area for aprosodia.

In a comprehensive investigation of the production of prosody, Baum and Pell [35] tested RHD and LHD patients and normal controls on their ability to produce both linguistic (declarative, interrogative, and imperative) and affective (happy, angry, and sad) prosody. Based on their acoustic analyses, Baum and Pell concluded that both patient groups were generally able to signal both linguistic and affective sentences similar to normal controls. However, when specific acoustic parameters of prosody were reviewed,

they found that the RHD group exhibited some problems controlling F_0 . For example, in the sentence repetition task, RHD patients' F_0 range in both linguistic and affective stimuli was restricted relative to LHD and normal subjects, while LHD subjects' range fell between that of RHD and normal subjects. This latter result could suggest that the right hemisphere is responsible for controlling F_0 , thus, providing evidence for the acoustic account. Similarly, Pell [36] found that RHD patients had difficulty controlling F_0 . In his study, 10 RHD patients and 10 normal controls were instructed to produce sentences with different affective moods (angry, sad, happy, neutral), linguistic modalities (question, statement), and sentential focus (initial, final, none). Speech samples were elicited from a story completion paradigm in which subjects read stimulus sentences after they were presented stories of appropriate contexts. It was found that RHD patients had less F_0 variation relative to normal controls across stimulus types. Furthermore, listeners were less able to identify affects and sentential focus conveyed by RHD patients. The fact that RHD patients' deficits were not restricted to affective stimuli provides evidence for the acoustic account.

Perception. Tucker et al. [30] compared LHD patients and RHD patients on their ability to identify and discriminate sentences that differed in affective moods (angry, happy, sad, or indifferent). They found that the RHD group performed significantly more poorly than the LHD group in both tasks; thus, they argued that the right hemisphere is specialized for the perception of affective prosody. However, no nonaffective stimuli were used, and the possibility that the right hemisphere is responsible for perception of all (affective and nonaffective) prosody cannot be ruled out. Heilman et al. [37] conducted a similar study in which RHD and LHD patients were asked to identify the affective moods of the stimulus sentences and to identify the semantic content of the stimuli by pointing at the appropriate pictures. Heilman et al. found that the RHD patients performed more poorly than LHD patients in identifying affective moods but that all patients performed perfectly on the semantic task. Because the latter task did not require the identification of prosody, no nonaffective prosodic task was included in this study as a control condition. The results from this study, therefore, might not indicate a problem of processing affective pitch variations alone after right hemisphere injury.

Subsequently, Heilman et al. [38] conducted a study in which RHD and LHD patients and normal controls were asked to identify both affective and nonaffective prosody. The affective condition consisted of stimulus sentences that varied in happy, sad, and angry prosodic patterns, and the nonaffective condition consisted of stimulus sentences that varied in declarative, interrogative, and imperative prosodic patterns. All stimulus sentences were low-pass filtered, resulting in removal of most segmental (consonant and vowel) information but preserving pitch and other prosodic structures. When the results were pooled across tasks, Heilman et al. found that both patient groups performed more poorly than the normal controls, but the RHD group was the most impaired. *Post hoc* analyses suggested that while RHD subjects did not differ in their perception of affective and nonaffective prosody, the LHD subjects performed worse in the nonaffective task. Furthermore, the RHD group performed worse than the LHD group in perceiving affective stimuli, but there was no between-group difference for the nonaffective task. These latter results provided some evidence for the functional account.

In a study investigating the effect of brain lesion on verbal and nonverbal emotional communication, Blonder et al. [39] also examined the ability of LHD patients, RHD patients, and normal controls to discriminate nonaffective prosody (question vs. statement) and to discriminate and identify affective prosody (happy, angry, sad, frightened, and neutral). They found that when the results from each individual task (e.g., discrimination of affective

prosody) were analyzed, RHD group was impaired in all tasks relative to the LHD. These findings provided evidence for the acoustic account of hemispheric specialization. Unfortunately, Blonder et al. [39] did not provide statistical analyses comparing within group performance, and thus it is unclear whether LHD patients identified affective prosody better than nonaffective prosody as in the Heilman et al.'s study. Nevertheless, some statistical analyses were conducted in both studies. Both studies found that RHD patients were more impaired in perceiving affective stimuli, but while Heilman et al. found that the two patient groups performed similarly in the nonaffective task, Blonder et al. found that the RHD group was more impaired. The reasons for the discrepancy is not apparent. Both studies used a similar number of subjects, although the Heilman et al.'s study did use three less subjects which may have limited statistical power. The Heilman et al.'s study required subjects to identify one more type of nonaffective prosody (i.e., imperatives) than the Blonder et al.'s study which should have made it a more sensitive test, but it was the Heilman et al.'s study in which no group difference was found. There was one more difference in the results of the two studies. Unlike the Heilman et al.'s study [38] in which both patient groups performed more poorly than normal controls, Blonder et al. [39] found that LHD patients performed similarly to normal controls. The discrepancy could be due to the different stimuli used in the two studies. LHD subjects' relatively poorer performance in the Heilman et al.'s study might be due to the use of low-passed filtered speech. LHD subjects may have had more difficulty identifying stimuli that were somewhat degraded and unnatural.

Van Lancker and Sidtis [40] conducted a study in which RHD and LHD patients were asked to identify affective stimuli. Unlike the studies mentioned above which did not examine the contribution of each type of acoustic cue in the stimuli, Van Lancker and Sidtis analyzed the acoustic features of their stimuli. They found that although both patient groups performed similarly, the RHD group made significantly more errors in perceiving sentences that used pitch as the acoustic cue to distinguish different affective moods, while the LHD group made more errors in perceiving sentences using duration as a cue. This study, thus provided evidence for the acoustic account of hemispheric specialization. However, it is noteworthy that only affective stimuli were used in this study. It is uncertain whether the subjects would have performed similarly, when identifying linguistic stimuli.

Pell and Baum [28,29] examined the ability of RHD and LHD patients to identify affective in addition to nonaffective stimuli, and they performed analyses similar to the Van Lancker and Sidtis [40] study. Pell and Baum [28] found that both LHD and RHD patients were able to perceive affective prosody as well as normal controls. However, the two patient groups, which did not differ significantly, performed worse than the normal controls in perceiving nonaffective stimuli. Furthermore, *post hoc* analyses showed that the LHD group was the only group who identified affective stimuli better than nonaffective stimuli; no such within-group difference was found in either than RHD or the normal group. These results provided some support for the functional account. Pell and Baum [29] then analyzed errors made by the LHD and RHD groups and found that unlike the results of Van Lancker and Sidtis, RHD and LHD patients did not differ in utilizing pitch and duration cues to distinguish the stimuli. One reason for the different results could be that fewer subjects were used in the Pell and Baum study (9 RHD and 10 LHD subjects) than in the Van Lancker and Sidtis study (13 RHD and 24 LHD subjects) and the ability to detect a possible difference was limited.

In an attempt to better understand the role of the different acoustic cues in the perception of prosody, Pell [41] used affective stimuli that were duration neutral and pitch neutral, and stimuli that con-

tained full cues (both pitch and duration cues). The results showed that when perceiving stimuli that contained full cues and stimuli that were duration neutralized (requiring subjects to rely only on pitch), the RHD and LHD groups did not perform differently. But both groups performed worse than normal controls. Furthermore, only the LHD group performed more poorly than normal controls when perceiving pitch-neutral stimuli, suggesting an impairment in using duration cues to perceive affective prosody. Results from this study suggest that both hemispheres are involved in perceiving affective prosody; however, the two hemispheres could be differentially specialized for processing different acoustic cues that are used in prosody. In spite of this, there was no evidence from this study suggesting a right hemispheric dominance for pitch perception because both RHD and LHD groups performed equally poorly with the duration-neutral stimuli. It is noteworthy that there are also studies which suggest the two hemispheres do not differentially process acoustic cues, and thus weakening the acoustic hypothesis. In a DC-potential study, Pihan et al. [42] measured the DC components of the EEG signals while subjects identified the affective moods of sentences that were either duration neutral or F_0 neutral. Pihan et al. [42] found that the processing of both types of stimuli yielded a similar pattern of DC potentials that were significantly lateralized to the right hemisphere. In addition, lesion studies such as Baum et al. [43] and Pell [36] show that RHD patients are impaired in the production and perception of timing cues in speech.

The investigation of hemispheric specialization of affective prosody also includes dichotic-listening studies. Ley and Bryden [44] asked normal subjects to identify the affective mood and semantic content of stimulus sentences and found an LEA (suggesting a right hemispheric specialization) for affective moods and an REA for semantic content. However, similar to some of the studies mentioned above, no stimuli varying in nonaffective prosody (e.g., statements vs. questions) were used. In a more comprehensive study, Luks et al. [45] included both affective and nonaffective stimuli and found an LEA for processing affective intonation but no-ear advantage for processing nonaffective intonation. In the second experiment of the study, subjects identified the affective moods of the nonaffective stimuli used in the first experiment and still found an LEA. Luks et al. [45] concluded that their results show that the task demands (i.e., functions), not acoustic features of the stimuli, determines hemispheric specialization.

A number of neuroimaging studies have been conducted to investigate neural correlates of affective prosody processing. In a PET study, George et al. [46] asked normal subjects to identify the emotion of stimulus sentences based on their intonation or content. The intonation and the content of some of these sentences were incongruent. George et al. found that identifying the content of the stimulus sentences activated prefrontal cortex bilaterally, more on the left side. On the other hand, identification of the intonation of the same sentences activated the right prefrontal cortex. In another PET study, Imaizumi et al. [47] asked subjects to identify the emotion and the speaker identity of semantically neutral words produced by professional actresses and actors. Both tasks required prosody processing. Imaizumi et al. found that both tasks activated multiple brain areas in both hemispheres which led them to conclude that the right hemisphere might not necessarily be dominant for prosody processing. Similarly, in an fMRI study specifically designed to evaluate lateralization of affective prosody and linguistic prosody processing, Stiller et al. [48] did not find the overall brain activities in the two hemispheres to be different across tasks. More recently in another fMRI study, Buchanan et al. [49] asked subjects to detect either the intended intonation of single-words (e.g., happy), or the identity of the words (e.g., "power"). The emotion detection task activated right inferior frontal gyrus, right inferior parietal lobe, and left cingulate gyrus. The

word detection task activated the left inferior frontal gyrus, the left middle temporal gyrus, and the right lingual gyrus/cuneus. These results suggest that affective prosody is predominately processed by the right hemisphere. It is noteworthy that Imaizumi et al. also found right inferior frontal gyrus activation in their emotion identification task. The inferior frontal gyrus has been shown to be related to pitch processing (e.g. [15]). Similar to some of the lesion studies reviewed above, these studies did not include stimuli varying in linguistic prosody. Thus, the notion of right hemispheric “dominance” for affective pitch processing cannot be established based on these results.

Summary of findings in affective prosody. I have reviewed studies investigating the perception and production of affective prosody, some of which also investigated nonaffective/linguistic prosody. Many researchers (e.g. [30,32] and Heilman et al. [37]) claimed that the right hemisphere is specialized for affective prosody (and affective prosody only). However, in many of these studies, either no LHD patients were included in the investigation or no nonaffective stimuli were used. Furthermore, inconsistent results were seen even in more carefully controlled studies possibly due to the use of different number and type of subjects (e.g., some studies have a smaller sample size which could have led to a smaller statistical power) and the use of different stimuli (e.g., some studies used natural speech while some used low-pass filtered speech). Thus, it is premature to draw a conclusion beyond the observation that injury of the right hemisphere impairs subjects’ ability to produce or perceive affective prosody. The notion of right hemispheric *specialization* for affective prosody alone was not convincingly established. Consequently, there is less than convincing evidence for the functional account of hemispheric specialization of pitch.

A possible explanation for LHD patients’ poor performance with affective pitch patterns in some of the studies is that LHD patients are impaired with tasks that are verbally and articulatorily demanding. Almost all of the studies reviewed involve such tasks in addition to pitch production or processing. Thus, Ross et al. [50] tested both RHD and LHD patients on their ability to comprehend and repeat affective prosody (happy, sad, angry, surprised, disinterested, or neutral) that is embedded in sentence-length stimuli. These stimuli contained real words, monosyllables (e.g., ba, ba, ba), or “asyllables” (e.g., aaaaahhhh). They found that as the verbal and articulatory demands decreased (from real words to asyllables), LHD patients’ ability to comprehend and repeat prosody increased. This was not the case with RHD patients. It seems that LHD patients did have more problems with tasks that were verbally and articulatorily demanding. However, without testing subjects’ performance on nonaffective prosody, the notion of right hemispheric specialization for affective prosody still cannot be established. It is possible that the same patterns of result could be found if subjects were asked to produce and comprehend nonaffective prosody of various verbal and articulatory demands.

Nonaffective/Linguistic Prosody at the Sentence Level

Besides being used to signal affect, pitch is also used in an utterance to mark grammatical/nonaffective differences. For example, there is a falling pitch pattern from the beginning to the end of a declarative sentence, and in contrast there is a rising pitch pattern in a question. In this section, I will review studies examining the production and perception of nonaffective/linguistic prosody used at the sentence level.

Production. Danly and Shapiro [51] and Danly et al. [23], respectively, investigated the production of sentences by Broca’s (nonfluent) and Wernicke’s (fluent) aphasics. Specifically, they examined the pitch declination of declarative sentences produced by LHD patients. Both studies found that pitch produced by the LHD patients was significantly different from pitch produced by nor-

mal controls. Ryalls [24] found similar results in French Broca’s aphasics. No RHD patients were included in these studies and, therefore, they could not conclude whether the impairment found in the LHD group was due to the specific left hemisphere injury or due to a more general cerebral injury. Furthermore, without affective stimuli, it is difficult to conclude whether the effect found was specific to nonaffective stimuli or to all stimuli that require the use of pitch. In a more recent study of production of nonaffective prosody by LHD patients, Seddoh [52] found the performances of the LHD and the control group to be comparable. In addition to using both fluent and nonfluent LHD patients, Cooper et al. [53] included RHD patients in their study. Cooper et al. concluded that the LHD group had more problems controlling pitch in declarative sentences of various length than the RHD group; however, no statistical analysis was provided to determine whether the difference observed was significant. Furthermore, RHD patients’ performance was sometimes intermediate between fluent and nonfluent patients’ performances. For example, RHD patients’ mean F_0 was between that of fluent and nonfluent patient.

To examine the right hemisphere’s involvement in control of nonaffective pitch, Weintraub et al. [21] asked RHD patients to produce and repeat declarative and interrogative sentences. They found that relative to normal controls, RHD patients were more impaired as judged by a rater. Similarly, Behrens [54] tested RHD patients’ production of declarative and imperative sentences, yes–no questions, and wh-questions. He found that abnormal pitch contours were present in most types of sentences produced by the RHD group, relative to normal controls, which suggests a pitch control deficit after right hemispheric injury. Combined with the studies mentioned above [23,24,51], this study seems to suggest that the control of pitch at the sentence level is impaired as a result of neurological injury in general. However, it is difficult to determine from these studies which hemisphere is dominant. Ryalls et al. [55] conducted a similar study but did not replicate the Behrens [54] results. Ryalls et al. [55] asked French RHD patients to repeat declarative sentences of various length produced by the investigator. They did not find the patients’ use of pitch to be different from normal subjects’. The discrepancy between this study and Behrens’ study may be due to the fact that this study required subjects to repeat what the investigator said, which could have aided their pitch production. Furthermore, declarative sentences of French and English have different pitch contours. It is possible that French declarative sentences were less difficult for RHD patients to produce.

As mentioned previously, Ryalls [24] found that French Broca’s aphasics were impaired in their production of declarative sentences. Taken together with the Ryalls et al. [55] results, this finding indicates that linguistic prosody is lateralized to the left hemisphere, thus supporting the functional account. Broca’s aphasics’ (non)fluency problem did not appear to influence the results because Wernicke (fluent) aphasics were found to have a similar problem with declarative sentences [23].

Perception. Few studies investigating the perception of pitch used in language examined nonaffective prosody in the absence of affective prosody. Therefore, almost all studies relevant to this section have already been reviewed. One study that examined nonaffective prosody at the sentence level without examining affective prosody was conducted by Weintraub et al. [21]. They tested RHD and normal subjects’ ability to discriminate declarative and interrogative sentences and found that the RHD patients were more impaired. Adding an LHD group, Bryan [56] found that RHD patients were more impaired than LHD and control groups, supporting that the right hemisphere is important even for nonaffective prosody. Another study that examined nonaffective prosody at the sentence level was conducted by Perkins et al. [57]. RHD, LHD, and control subjects were asked to identify or discriminate sentences with in-

tonational contours that distinguish questions from statements, or intonational contours that mark different syntactic phrase boundaries in several experiments. In one experiment, the stimuli were low-pass filtered to take away segmental information. In no experiments were RHD and LHD patients performed significantly differently, although one patient group was sometimes different from the control group. Furthermore, in most experiments, all subjects performed highly accurately (over 90% accuracy). Using magnetoencephalography (MEG), Imaizumi et al. [58] asked subjects to count the number of occurrences of single word stimuli differing in linguistic prosody (question vs. statement) or final vowel. They found left lateralization in the phoneme task but bilateral activity in the prosody task. No affective stimuli were included in this study.

Summary of findings in nonaffective prosody. Relatively few studies have been conducted to examine the production and perception of nonaffective prosody. In the seven production studies reviewed, no definite conclusions could be drawn as to which hemisphere is dominant for nonaffective pitch. Three of the production studies compared LHD patients and normal controls, and all of them found LHD patients to have F_0 impairment. Three studies compared RHD patients and normal controls, two of them found RHD patients to be impaired. In the one study that investigated both RHD and LHD patients, RHD patients seemed to perform intermediate between fluent and nonfluent LHD patients in F_0 measures, although no statistical analyses were provided. Seven perceptual studies were conducted, and the results were mixed.

Phonemic Stress and Contrastive/Emphatic Stress

It has been argued that hemispheric specialization of language is determined by neither acoustic cues nor their functions but rather by the length of an utterance. More specifically, Gandour [59] proposed that the right hemisphere is specialized for pitch variations that extend to a larger temporal domain (e.g., sentences), and the left hemisphere is specialized for pitch variations that are shorter in duration (e.g., syllables). Therefore, it is important to look at how the two hemispheres control and process pitch patterns both at the sentence and word levels. In this section, studies of the production and perception of phonemic and contrastive/emphatic stress patterns will be reviewed.

Production. Emmorey [60] examined the production of phonemic stress in six RHD patients and seven LHD patients, including two fluent and five nonfluent patients (more subjects participated in this study, but these were the subjects whose data were analyzed). Subjects were asked to produce words that use stress to contrast between noun compounds and noun phrases (e.g., GREENHOUSE vs. green HOUSE). Emmorey found that the LHD group used pitch to distinguish noun compounds from phrases less often than the RHD group. Furthermore, listeners judged the stress patterns produced by the RHD group to be less impaired. However, acoustic analyses of individual subjects showed that none of the nonfluent patients (0%), four out of six of the RHD patients (67%), and one out of the two fluent patients used pitch to signal stress (50%). Because more fluent subjects than nonfluent subject used pitch to signal stress, the results observed could be explained by subjects' fluency deficit rather than their unilateral hemispheric deficit. More fluent subjects are needed to gain a better understanding of how fluency deficits might have influenced the results. In fact, in studies of tone languages which I will review in more detail in the next section, RHD patients' tone production performance was between fluent and nonfluent aphasics', which could suggest a fluency rather than a hemispheric specialization effect. Nevertheless, this study provided some evidence for the left hemisphere specialization for phonemic stress, and thus for the functional account.

In addition to examining phonemic stress as in the Emmorey [60] study, Behrens [61] examined eight RHD patients' produc-

tion of contrastive stress. In the contrastive stress production task, subjects were asked to produce sentences emphasizing one of the words (e.g., "Sam hated the movie."). The phonemic stress production task was similar to Emmorey's study. Behrens found that the patients as a group produced fewer acoustic cues (including pitch) in contrastive stress than normal subjects. Although this general acoustic difference did not reach statistical significance (possibly due to the small number of subjects), RHD patients were found to produce a statistically significantly higher mean F_0 (pitch) than the normal controls. Furthermore, normal listeners judged the patients' production to be less salient than normal, although no statistical analyses were provided. Behrens claimed that this study provided evidence that linguistic prosody is intact after right hemispheric injury. However, without testing an LHD patients group, and with some evidence of pitch impairment shown by the RHD group, the possibility of a right hemispheric influence on pitch production in phonemic and contrastive stress cannot be ruled out. Weintraub et al. [21] also included an experiment investigating RHD patients' production of contrastive stress in their study and found that RHD patients' were more impaired relative to normal controls. This study shows that RHD patients' could be impaired in producing nonaffective prosody at the word level, which provides evidence for the acoustic account.

More recently, Ouellette and Baum [62] investigated nonfluent LHD and RHD patients' production of phonemic and contrastive stress. Acoustical analyses showed that the use of pitch and amplitude to encode stress by both groups was similar to that of normal controls. Thus, no evidence was provided for either account from this study. However, the LHD group had a problem using duration in stress, suggesting that different acoustic cues may be differentially processed by the two hemispheres.

Perception. Blumstein and Goodglass [63] examined nonfluent and fluent LHD patients' perception of phonemic stress. Subjects identified pictures representing words that differ minimally in stress (e.g., whitecap vs. white cap, and a convict vs. to convict). Blumstein and Goodglass found that fluent and nonfluent subjects did not differ from normal subjects nor from each other. Using a subset of the stimuli used by Blumstein and Goodglass [63], Weintraub et al. [21] tested RHD patients' ability to perceive phonemic stress and found that they were impaired relative to normal controls. In addition, they found that RHD patients were impaired in perceiving contrastive stress. Emmorey [60] used RHD patients in her study in addition to LHD patients (both fluent and nonfluent) and found that while LHD patients performed worse than their normal matches, RHD patients and their normal matches did not differ in their performance. The stimuli used in the Blumstein and Goodglass study were also used in the Emmorey study; however, modifications were made so that the task was simplified. Emmorey suggested that the simpler task may have been more sensitive in differentiating between the LHD and normal groups. Furthermore, the conflicting results between this study and the Weintraub et al. study may be due to the subset of stimuli chosen.

To investigate the involvement of individual acoustic cues in phonemic and contrastive stress perception and how they relate to hemispheric specialization, Baum [22] used three sets of stimuli which varied in different acoustic parameters for each stress type. The first set used only pitch (duration neutral) as an acoustic cue to signal phonemic and contrastive stress, the second set used only duration (pitch neutral), and the last set used both cues. With regard to the phonemic stimuli, the LHD group and the RHD group did not differ in their perception of duration-neutral stimuli, although both groups were worse than normal controls. This suggests that their ability to utilize pitch to perceive phonemic stress did not differ. All groups performed significantly better in judging contrastive stress than in judging phonemic stress. Normal controls were

better at perceiving all three sets of contrastive stress relative to the LHD group. Unfortunately, no information was given by the author regarding whether RHD subjects' performance was significantly different from the other two subject groups. Interestingly, despite the fact that contrastive stress and phonemic stress are functionally different, the LHD group was the only group that performed at chance level for both phonemic and contrastive pitch-neutral stimuli (i.e., they failed to utilize duration), suggesting that acoustic cues could be differentially processed by the two hemispheres regardless of their functions. Furthermore, half of the subjects in the RHD group scored lower in the duration-neutral stimuli than in the pitch-neutral stimuli for both phonemic and contrastive stress stimuli, suggesting a pitch perception deficit. Although the major findings in this study supported neither accounts of hemispheric specialization of pitch, these latter findings provided some support for the acoustic account.

Dichotic-listening method was also used to study phonemic stress perception. Behrens [64] asked subjects to identify stress placement in real word minimal stress pairs (e.g., HOTdog vs. hot-DOG), in low-pass filtered words, and in nonsense words. REA was observed, when subjects were listening to real words. LEA was observed, when subjects were listening to filtered speech, while no-ear advantage was found with nonsense words. Behrens argued that as the linguistic significance of stress increased in the stimuli, a left lateralization was observed. However, that was also when lexical processing occurred, which was confounded with the results.

Summary of findings in phonemic and contrastive stress. Studies investigating the production and perception of phonemic and contrastive stress yielded mixed evidence concerning hemispheric specialization of pitch. Some studies appeared to provide evidence for the functional account (e.g. [60]), while others appeared to provide evidence for the acoustic account, although the authors did not necessarily interpret their results as such (e.g. [61]). Yet other studies provided evidence consistent with neither accounts (e.g. [62]).

Summary of Studies of Nontonal Pitch Patterns

In reviewing lesion studies and dichotic-listening studies in nontone languages, I found that many of the studies lacked either suitable control subjects or sufficiently comprehensive sets of stimuli. Results from these studies showed that sometimes the left hemisphere appears to be dominant for the production and perception of pitch, sometimes the right hemisphere, sometimes both, and sometimes neither, depending on the experimental stimuli and procedures and the groups of patients tested.

The mixed results from these studies could be related to the heterogeneity of the patient population. Even an injury within the same hemisphere can result in very different symptomatology because of the different locations of injury within the hemisphere. The lesion studies reviewed either did not report subjects' specific locations of injury or included subjects, who had different lesion locations. Of the studies that reported specific locations of injury within a hemisphere, almost none discussed how the different injury locations could affect behavioral performance. Furthermore, none of the studies reviewed included more than 24 patients in each hemisphere-damaged group. Most included between 5 and 10 subjects per group; thus, only a few subjects had lesions in similar areas within a hemisphere.

NEUROLOGICAL STUDIES OF LEXICAL TONES

In this section, I will discuss relevant neurological studies examining lexical tones, pitch patterns that are used to contrast word meaning. Studies examining pitch accents, which are closely related to lexical tones, will also be reviewed. Not being reviewed

here are studies of tone languages investigating other aspects of language, for example, vowel duration in Thai [65].

Similar to studies investigating nontone languages, the lesion approach has been the most in neurological studies of lexical tones. Gandour and Dardarananda [66] asked LHD subjects to identify words that differed minimally in the five Thai lexical tones. They found that LHD patients were less competent at identifying Thai tones relative to one normal and one RHD subjects. The small number of control subjects tested in this study makes it very difficult to conclude that the left hemisphere is specialized for tone perception. In addition to five LHD patients, Eng et al. [67] included five normal control subjects. They found that LHD patients could not perceive tones as accurately as normal listeners. However, as in some of the nontone studies and the Gandour and Dardarananda [66] study, no RHD patients were tested. Whether the results were due to a general neurological deficit or to a specific left hemispheric deficit cannot be determined.

Another tone perception study conducted by Hughes et al. [68] found that Mandarin-speaking RHD patients were impaired relative to normal controls in their perception and production of affective prosody, but their ability to identify tones was intact. However, the affective stimuli in this study consisted of sentences and the tone stimuli were individual words. The results could suggest an impairment in monitoring pitch at a more global level, rather than indicating a differential deficit in affective and tone processing. Furthermore, both patient and normal groups performed near ceiling in perceiving tones. It is possible that the experimental task was not sensitive enough to detect group differences.

When combined with results from the Eng et al.'s study [67], the results from the Hughes et al.'s study [68] showing RHD patients' normal tone perception performance could suggest a left hemispheric dominance for tone perception. However, the experimental tasks in the two studies varied in the degree of difficulty. In the Eng et al.'s study, subjects were asked to listen to one stimulus and to identify one of the five pictures corresponding to the words that varied minimally in the five Toisanese tones. In the Hughes et al.'s study, subjects were also asked to listen to one stimulus and identify the appropriate picture, but they had to choose from four pictures, only two of which represented words of minimal tonal difference. Quite possibly, the reason why the RHD subjects could perform well in the tone identification task in the Hughes et al.'s study was that the task was easy. LHD could possibly perform well in such task. In order to resolve this issue, a study testing both RHD and LHD patients on the same tasks is needed.

A number of studies investigating tone production after brain injury were also conducted. Packard [69] asked LHD patients to produce Chinese syllables and found that the number of tone errors and consonant errors did not differ as rated by normal listeners. Hence, Packard argued that just like consonant production, tone production is governed by the left hemisphere. However, no RHD patients were included in the study. Ryalls and Reinvang [70] examined the production of Norwegian pitch accents produced by five nonfluent LHD and five RHD patients. Subjects were asked to produce tone pairs, acoustical measurements were obtained and showed that LHD patients' productions were significantly different from RHD patients' productions. Because there was only one normal speaker, statistical analyses directly comparing the three groups could not be performed. It is quite possible that both RHD and LHD groups were impaired, but the LHD patients were more impaired. As a matter of fact, the raw scores given by the authors did show that RHD's performance was intermediate of the one normal speaker and the LHD patients.

Gandour et al. [71,72] also examined brain-injured patients' tone production. Gandour et al. [71] asked six aphasics (one of which is left-handed), one RHD, one dysarthric, and five normal

subjects to produce Thai words that differed minimally in tones. They found that normal listeners were able to identify tones produced by the normal speakers nearly perfectly while the identified four out of the six aphasics at over 90% accuracy, and the RHD and dysarthric subjects at over 92% accuracy. Statistical analyses were not conducted to specifically compare LHD and RHD patients. Nonetheless, most LHD patients' and the one RHD patients' performances seem to be too high to conclude that one particular hemisphere is specialized for tone production. In another tone production study including more subjects and dividing the LHD subjects into fluent and nonfluent groups, Gandour et al. [72] found that RHD patients' performance was intermediate to fluent and nonfluent LHD patients' performances, with the nonfluent LHD patients' performance being the most impaired. The latter results suggest that poor performance could be due to subjects' fluency deficit rather than to their hemispheric deficit. Furthermore, it should be noted that nonfluent LHD patients are usually apraxic (e.g. [73]); thus, their deficit in producing the segments might interfere with their ability to produce appropriate pitch variation even if this ability was intact. As mentioned earlier, Ross et al. [50] found that LHD patients were more impaired with producing and comprehending pitch patterns that were verbally and articulatorily demanding. Although Ross et al. only used nonaffective stimuli, the same patterns of result could be found with linguistic stimuli.

In a tonal coarticulation study examining bisyllabic and short phrases coarticulation, Gandour et al. [74] reported that RHD and LHD patients exhibit essentially the same patterns of tonal coarticulation, which are largely intact. However, in a later study investigating tonal coarticulation embedded in a carrier sentence, Gandour et al. [75] found that LHD patients, especially nonfluent patients, were severely impaired relative to RHD patients whose productions were similar to normal speakers' productions. This study seems to suggest that the left hemisphere is responsible for tone production that is highly coordinated.

Yiu and Fok [76] conducted a study investigating the production and perception of lexical tones by Cantonese-speaking aphasics. Eleven anomic, two Wernicke's, two Broca's, and four transcortical motor aphasics were asked to identify pictures representing six Chinese words that differ minimally in the six Cantonese tones. The results showed that the 21 aphasics performed significantly more poorly than the 11 normal controls. Aphasics were further grouped into fluent (anomic, conduction, and Wernicke's aphasics; $n = 15$) and nonfluent (Broca's and transcortical motor; $n = 6$) subgroups. The two aphasics subgroups did not differ in the identification performance. In the production portion of the study, subjects produced the same list of words that was used as stimuli in the perceptual experiment. One native Cantonese-speaking experimenter judged the subjects' productions according to tonal and segmental errors. It was found that normal subjects produced the less tonal errors relative to the fluent aphasics, who produced less tonal errors than the nonfluent aphasics. Furthermore, it was found that the nonfluent group produced a greater variety of errors than the fluent group. These results show that aphasics' fluency significantly influences their tonal production as suggested earlier. Similar to the previous studies, without an RHD group, it is difficult to conclude that the left hemisphere is specialized for tone production and perception.

In a study using Swedish stimuli, Bradvik et al. [26] found that RHD patients did not differ from normal subjects in perceiving affective prosody, pitch accents, and phonemic stress, and did not differ in their production of affective prosody. However, in a subsequent study which included additional tasks, Bradvik et al. [77] found that RHD patients had an impairment, relative to normal subjects, in producing pitch accents, identifying and producing prosody at the phrase level, identifying contrastive stress, and

identifying emotions. Although no LHD patients were used as subjects in these two studies, they provided some evidence that the right hemisphere is important for both affective prosody and linguistic pitch contrasts.

There were also studies of tone languages that did not investigate tone perception and production *per se*. For example, Gandour et al. [78] found that Thai RHD patients had problems producing affective prosody; however, no LHD patients were included, and no nonaffective stimuli were used. Ross et al. [79] found that Taiwanese-speaking RHD subjects had problems, relative to normal controls, using F_0 to distinguish various affects; however, no LHD subjects and no nonaffective stimuli were included.

In addition to lesion studies, a number of dichotic-listening studies were conducted to investigate the involvement of the two hemispheres in tone perception. Van Lancker and Fromkin [80,81] asked Thai and English subjects to identify Thai words that varied in tone, and also hummed versions of the same words. They found that only the Thai subjects, when listening to Thai words, showed an REA, indicating left hemispheric specialization for tone perception. No significant-ear advantage was found, when subjects were presented with the hummed stimuli. Van Lancker and Fromkin argued that these results were indicative of a left hemispheric dominance for tone processing. However, the condition in which the Thai subjects listened to Thai words was the only one in which subjects heard meaningful words. Thus, the results could be explained by a word listening effect rather than a tone perception effect. Moen [82] found similar results in his study using Norwegian pitch accents. Woerner [83] asked Thai- and German-speaking subjects to identify Thai words differing in tones and the same pitch patterns superimposed on square waves. Woerner found an REA significant at the $p > 0.1$ level for both types of stimuli for the Thai group while no-ear advantage was found in the German group. He argued that the results not only support a left hemispheric specialization for tone processing, but that tone processing is not preceded by "... a top-down evaluation of whether or not the perceived stimulus is of a linguistic nature." If what Woerner [83] argued is correct, an REA should also be observed in the Van Lancker and Fromkin [80] study, when Thai listeners were presented with the hummed versions of the Thai words. Alternatively, Woerner should demonstrate how the non-top-down nature of tone processing and left lateralization is only construed by square waves, but not hums.

Besides Thai tones, Mandarin tones were also investigated in dichotic-listening studies. Baudoin-Chial [84] asked French- and Mandarin-speaking subjects to identify Mandarin consonants, tones, and hums. No ear preference was found for any of the stimuli for the Mandarin group. For the French group, an REA, LEA, and no-ear advantage found for the consonants, tones, and hums, respectively. More recently, Wang et al. [85] conducted another dichotic-listening study of Mandarin tones. They argued that the absence of an REA for tone processing in the Baudoin-Chial's study might be related to a ceiling effect, i.e., the stimuli were not challenging enough. In their study, Wang et al. presented Mandarin words differing in tones to Mandarin- and English-speaking subjects, who were asked to identify the tone of the stimuli. English subjects were provided with a training program for this task as they had no knowledge of Mandarin Chinese. To increase the difficulty of the task and to avoid a ceiling effect, stimuli were embedded in noise and were presented rapidly to the subjects. Wang et al. found that an REA for tone identification was only present in the Mandarin-speaking subjects, providing evidence for left hemispheric specialization for tone processing. However, as suggested before, the REA found in this study could be related to general word processing rather than tone processing, similar to the Van Lancker and Fromkin studies. Ip and Hoosain [10] also

conducted a dichotic-listening study of Chinese words; however, the study was not designed to test perception of lexical tones but general Chinese word processing.

More recently, neuroimaging experiments using PET were conducted to investigate hemispheric specialization of tone perception in Thai. In a study by Gandour et al. [86], 10 subjects, 5 Thai speakers and 5 English speakers, participated in three stimulus conditions: baseline, pitch, and tone conditions. In the baseline condition, no stimuli were presented to the subjects; they were instructed to relax, and no overt motor response was required. In the pitch and tone conditions, subjects were required to make discrimination judgments of pitch patterns and Thai tones, respectively, by clicking mouse buttons. Stimuli in the tone condition were Thai words. Stimuli in the pitch condition were the same as those used in the tone condition except that they were low-pass filtered (pitch contours were preserved but most segmental information was removed). Although all subjects were required to make pitch discrimination judgments in the latter two conditions, the tone condition was a linguistic condition only for the Thai speakers. A comparison of the results of the tone condition and pitch condition revealed an increase in rCBF in the left inferior frontal gyrus (Brodmann area 44/45, Broca's area) only in the Thai subjects. Gandour et al. argued that this is clear evidence for tone (i.e., linguistic pitch contrast) being lateralized to the left hemisphere because Thai tones were only linguistic for the Thai speakers, and an increase of rCBF was observed only in Thai speakers. However, a problem with this study is that for the Thai speakers, the stimuli in the tone condition were actual words. The results obtained in this study may simply reflect that the left hemisphere is specialized for processing meaningful words, regardless of the presence of linguistic pitch contrasts in these stimulus words. If tone perception were lateralized to the right hemisphere similarly to pitch perception, comparison of rCBF of these two conditions would have eliminated the right hemispheric activation. What remained in this comparison between the active tone and pitch conditions would have been the activation for perceiving consonants and vowels and meaningful words. Furthermore, if English speakers were presented English words and asked to discriminate pitch differences (every syllable carries pitch, although in English pitch is not linguistically contrastive), an increase of rCBF in the left hemisphere could very well be observed because stimuli in this case would be meaningful words to the English speakers. In the Gandour et al.'s study, the failure to observe an increase of rCBF in the left hemisphere of the English speakers may suggest only that listening to vowels and consonants alone did not cause an increase in brain activity in the left hemisphere that was as significant as in listening to meaningful words. In a later study including Chinese-speaking subjects, Gandour et al. [87] used a similar methodology and found similar potentially confounded results. Klein et al. [88] used a similar paradigm but investigated Mandarin- and English-speaking subjects discriminating pairs of Mandarin words. They found similar results. Instead of asking subjects to discriminate stimulus pairs, Hsieh et al. [89] asked Mandarin- and English-speaking subjects to discriminate the first and last syllables of a five-syllable Mandarin sequence in order to increase the retention of the stimuli in memory. The stimuli were Mandarin words differing in tones, consonants, vowels, and low-pass filtered Mandarin words differing in the same tonal patterns as the real words (pitch discrimination). Relative to when they were passively listening to the low-pass filtered stimuli without making overt judgments (passive listening), Mandarin-speaking subjects had increased rCBF in the left inferior frontal gyrus, when discriminating Mandarin tones. English-speaking subjects only showed cerebellar activations. Furthermore, pitch discrimination relative to passive listening, unlike tone discrimination, did not activate

left inferior frontal gyrus in both subject groups. These results are similar to their early findings and are confounded with lexical processing as discussed above. Unlike their previous studies, left premotor cortex activations were observed in this study in the pitch condition. Such activation was also observed in the tone, consonant, and vowel conditions in the Mandarin-speaking subjects and in the vowel condition in the English subject. Hsieh et al. argued that the clusters of activation running from the premotor cortex to Broca's area reflect "subvocal rehearsal processes that refresh the contents of a phonological buffer for temporary storage of phonological information." However, it is unclear how phonological processing is related to premotor activation without inferior frontal activation. Many nonlinguistic and nonauditory studies show premotor activations, for example, sequential movements [90]. It is possible that left premotor activations observed were related to subjects' motor response of the right hand. If so, it is unclear why the English subjects had such activation only in the vowel condition. Moreover, these results would be equally puzzling, if premotor activations were attributed to phonological processing.

In all of the dichotic-listening and functional neuroimaging studies of lexical tone processing reviewed in this section, the authors attempted to study how lexical tone processing, before or without the processing of word meaning, is lateralized in the brain. Throughout this section, I commented that lexical processing may be confounded with prelexical processing, which was what many investigators attempted to study. While it is difficult to separate lexical processing from tone processing, an experimental condition which can potentially put my concern to rest is to have listeners discriminate English word pairs differing in pitch in addition to discriminating Mandarin word pairs differing in tone. If word processing is indeed confounded with tone/pitch processing, left inferior frontal activations or REA should be observed, when English listeners discriminate pitch patterns in English words, similar to when Mandarin listeners discriminate tonal patterns in Mandarin words, even though pitch patterns are not lexical in English but are so in Mandarin.

Summary of Studies of Lexical Tones

Most of the lesion studies involving tone languages focused on tone production and perception in LHD patients. Except for those conducted by Bradvik and coworkers, few studies comprehensively investigated the results of tone perception and production after right hemispheric injury and compared the results with the production and perception of nonlinguistic/affective stimuli. Unfortunately, except for one study, no studies have been conducted to investigate comprehensively the performance of both LHD and RHD patients. Thus, it is difficult to conclude which hemisphere of the brain is specialized for tone processing and production. The only study that clearly demonstrates a greater tonal deficit in LHD patients relative to RHD patients involves tonal coarticulation in sentences [91], which requires monitoring the production of the entire sentence as well as more local and subtle changes, *both* segmental and suprasegmental (lexical tones, intonation, etc.). With regard to dichotic-listening studies, it is very difficult to study hemispheric specialization for tone perception that is independent of the perception of segments and meaningful words because tones always co-occur with segments. Finally, the existing evidence from neuroimaging studies does not offer fully convincing support for the functional account because of the problems noted. Therefore, it is reasonable to conclude that no study has shown that tone perception and/or production is affected *only* by a left hemisphere lesion nor is there convincing evidence that the right hemisphere is dominant for both tone and nontone production and perception.

CONCLUSION AND FUTURE RESEARCH CONSIDERATIONS

Studies investigating various types of pitch patterns used in language were reviewed. Although most researchers interpret their studies to be supportive of the functional account of hemispheric specialization of pitch processing, the current survey can only provide minimal evidence for this view. Furthermore, little evidence exists for the acoustic account. This is different from recent research in auditory (nonspeech) acoustics which showed hemispheric asymmetry in processing spectral (right hemisphere) and temporal (left hemisphere) cues [92], or a general right lateralization for both types of cues [93]. Hypotheses alternative to the two discussed were hinted in some of the studies reviewed. First, as suggested by Cancelliere and Kertesz [34], subcortical regions, especially the basal ganglia, may be responsible for processing pitch patterns used in language, especially affective pitch patterns. Some of the mixed results could be explained by lesions (and lack of lesions) of the basal ganglia (and connective tissues) in both LHD and RHD patient groups that were not reported. The second alternative hypothesis suggests that the two hemispheres are specialized for stimuli of different length. For example, the right hemisphere is specialized for pitch variations at the sentence level, while the left hemisphere is specialized for pitch variations at the syllable level [59]. This view is similar to the proposal by Poeppel [94] that the left and right hemisphere preferentially extracts auditory information of a shorter (25–50 ms) and longer (150–250 ms) temporal domain, respectively. It is also similar to the left-local, right-global distinction proposed by Ivry and Robertson [95] accounting for hemispheric differences in various auditory and visual perception tasks. However, regarding pitch processing, this view is yet to be supported. Thus far, results from both sentence and word level processing showed equally mixed results. The third alternative hypothesis suggests that the two hemispheres may contribute equally in pitch processing (e.g. [58]) or one hemisphere contributes to all pitch processing (e.g. [19]). Based on the current review, little evidence supports these views.

For future research, there are several important considerations. First, the comprehensiveness of the use of subjects and stimuli influences the interpretability of the results in the context of the two accounts; in particular, the use of both RHD and LHD subject groups and both linguistic and affective stimuli is especially important. Second, the heterogeneity/homogeneity of the subjects, especially in terms of their lesion sites, should be considered. Third, left hemisphere lesion relates to apraxia of speech and performance of verbal tasks. When testing LHD patients, it is important to consider how these factors may affect the production and comprehension of the embedded pitch patterns. Fourth, particularly for dichotic-listening studies and neuroimaging studies, how perception of actual words influences the perception of the embedded pitch patterns should be considered.

An understanding of the relationship between pitch processing and the brain not only can help us to understand the fundamentals of perception and cognition, but also how the brain is organized. This pursuit will not only involve innovative research methodology and technology but reexamination of our current knowledge and deficiencies. This article hopefully is a step forward.

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