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Unilateral Brain Damage, Prosodic Comprehension Deficits, and the Acoustic Cues to Prosody

MARC D. PELL AND SHARI R. BAUM

School of Communication Sciences and Disorders, McGill University, Montreal, Canada

Stimuli from two previously presented comprehension tasks of affective and linguistic prosody (Pell & Baum, 1997) were analyzed acoustically and subjected to several discriminant function analyses, following Van Lancker and Sidtis (1992). An analysis of the errors made on these tasks by left-hemisphere-damaged (LHD) and right-hemisphere-damaged (RHD) subjects examined whether each clinical group relied on specific (and potentially different) acoustic features in comprehending prosodic stimuli (Van Lancker & Sidtis, 1992). Analyses also indicated whether the brain-damaged patients tested in Pell and Baum (1997) exhibited perceptual impairments in the processing of intonation. Acoustic analyses of the utterances reaffirmed the importance of F0 cues in signaling affective and linguistic prosody. Analyses of subjects' affective misclassifications did not suggest that LHD and RHD patients were biased by different sets of the acoustic features to prosody in judging their meaning, in contrast to Van Lancker and Sidtis (1992). However, qualitative differences were noted in the ability of LHD and RHD patients to identify *linguistic* prosody, indicating that LHD subjects may be specifically impaired in decoding linguistically defined categorical features of prosodic patterns.

INTRODUCTION

The neurobehavioral literature on speech prosody is replete with disparate findings and currently fails to illuminate the cerebral mechanisms governing our receptive capacity for suprasegmental information. For example, many studies have reported a link between right unilateral brain lesions and a specific impairment in deriving the *emotional* meaning of intonation, indicating that the right hemisphere may be superior in the receptive processing of affective prosody (Blonder, Bowers, & Heilman, 1991; Bowers, Coslett,

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Bauer, Speedie, & Heilman, 1987; Ehlers & Dalby, 1987; Heilman, Scholes, & Watson, 1975; Heilman, Bowers, Speedie, & Coslett, 1984; Ross, 1981; Tucker, Watson, & Heilman, 1977). However, other studies have been unable to detect a disturbance for affective prosody in right-hemisphere-damaged patients (Bradvik, Dravins, Holtas, Rosen, Ryding, & Ingvar, 1990; Lebrun, Lessinnes, De Vresse, & Leleux, 1985; Pell & Baum, 1997), while investigations that have excluded patients with comparable *left* hemispheric dysfunction from their analyses do not warrant the conclusion that affective-prosodic cues are lateralized strictly to the right hemisphere in perception (Heilman et al., 1975; Ross, 1981; Tucker et al., 1977).

Further research has demonstrated that both left-hemisphere-damaged (LHD) and right-hemisphere-damaged (RHD) patients may be impaired relative to normal control (NC) subjects in the ability to process emotional-prosodic stimuli (Cancelliere & Kertesz, 1990; Schlanger, Schlanger, & Gerstman, 1976; Seron, Van der Kaa, Vanderlinden, Remits, & Feyereisen, 1982; Van Lancker & Sidtis, 1992), at least on certain experimental tasks (Tompkins & Flowers, 1985). The cerebral mechanisms underlying prosodic perception, therefore, may be more bilaterally represented than initially hypothesized (Van Lancker & Sidtis, 1992). Clearly, the neurological substrates of our receptive abilities for affective prosody have yet to be determined.

Similarly unclear at this time is the stage of processing at which prosodic impairments arise in the decoding of affective meaning. Some investigators have posited a disruption of nonverbal (affective) representations following unilateral hemispheric insult (Blonder et al., 1991), thus attributing prosodic abnormalities to a high-order impairment involving affective or cognitive processing. In contrast, others postulate the presence of a lower-level perceptual impairment and suggest that a misperception of the acoustic cues to prosody [fundamental frequency (F0), duration, and amplitude] in processing the auditory input stream contributes to the poor comprehension of affectively laden vocal stimuli by brain-damaged patients (Bowers et al., 1987; Robin, Tranel, & Damasio, 1990; Van Lancker & Sidtis, 1992).

The notion that brain-damaged patients have a more basic disturbance in analyzing the acoustic structure of sentence intonation is consonant with reports that these patients often show deficits in using the same auditory cues in *nonlinguistic* tasks. Right-hemisphere-damaged individuals have been noted to be particularly susceptible to errors on nonlinguistic tasks that require the processing of complex pitch information, indicating that this skill may rely predominantly on right-hemisphere auditory mechanisms (Robin et al., 1990; Sidtis & Volpe, 1988; Zatorre, 1988). Interestingly, a left-hemisphere bias has been proposed for the processing of *temporal* cues on similar nonlinguistic tasks (Carmon & Nachson, 1971; Robin et al., 1990).

If the auditory mechanisms that process spectral and temporal parameters of nonlinguistic stimuli are indeed differentially lateralized (Robin et al., 1990), significant ramifications in how *prosodic* stimuli are processed and understood by unilaterally brain-damaged patients may be anticipated. Since both fundamental frequency (Fairbanks, 1939; Ladd, Silverman, Tolkmitt, Bergmann, and Scherer, 1985; Lieberman & Michaels, 1962; Williams & Stevens, 1972) and duration (Fairbanks & Hoaglin, 1941) have been shown to be important cues in distinguishing vocally conveyed affect in normal speech comprehension, the misperception of one of these cues as a result of unilateral brain lesion could well lead to comprehension deficits for emotional prosody, particularly if the misperceived cue were crucial in distinguishing one emotion from another.

To examine the effects of unilateral brain damage on the perception of prosodic information, Van Lancker and Sidtis (1992) tested the abilities of LHD, RHD, and healthy control subjects to identify the emotional meaning conveyed by intonational cues from four possible alternatives (angry, sad, happy, surprised). Subsequently, the authors determined mean and variability measures of F0, amplitude, and duration from the stimuli; they then utilized discriminant function analyses to explore which of the acoustic cues served to signal the intended meanings of the stimuli, and which cues predicted the comprehension *errors* made by each clinical group on the identification task.

In these latter analyses focusing on the LHD and RHD subjects' errors, Van Lancker and Sidtis (1992) first determined the most frequent incorrect response observed for each stimulus for each group. The stimuli were then recategorized according to the most frequent substitution in order to examine which acoustic cues were associated with the misidentification. For example, a stimulus intended to convey ''joy'' but identified most frequently by one of the two patient groups as conveying ''sorrow'' was recoded accordingly; the full set of stimuli, reclassified according to each group's error responses, was then submitted to a discriminant analysis using the acoustic cues as independent variables. Thus, the authors could ascertain whether the specific pattern of errors made by each clinical group was predictable in terms of one or a combination of the acoustic parameters. Such findings could indicate whether the LHD and/or RHD subjects were impaired in their perception of the acoustic features of the stimuli.

The results of the comprehension task presented by Van Lancker and Sidtis (1992) revealed no significant differences between the left- and right-hemisphere-damaged groups, each of whom made significantly more errors than the control group in identifying the intended emotional meanings of the stimuli. Despite their similar level of impairment on this task, however, the analyses performed on subjects' errors suggested that LHD and RHD patients may have been using the acoustic cues to prosody differently in judging the affective meanings (Van Lancker & Sidtis, 1992); interestingly, a discriminant analysis of the LHD subjects' errors revealed that this group was basing its decisions on fundamental frequency information (particularly F0 variability), whereas an analysis of the RHD subjects' affective misclassifications indicated a reliance on durational cues in identifying the stimuli (Van

Lancker & Sidtis, 1992). These results suggested to the authors that receptive disturbances of emotional prosody are perceptual in nature, possibly reflecting the superiority of each hemisphere for the processing of different acoustic cues to prosodic meanings (Robin et al., 1990; Van Lancker & Sidtis, 1992).

It should be noted that the prosodic parameters of affective speech are also employed in communicating linguistic meaning, for example, to distinguish a statement from a question. Thus, the presence of a perceptual deficit for prosody (Robin et al., 1990; Van Lancker & Sidtis, 1992) may well have repercussions beyond the affective domain and result in a decrement in subjects' ability to comprehend nonaffective prosody (Baum, Daniloff, Daniloff, & Lewis, 1982; Heilman et al., 1984; Pell & Baum, 1997; Weintraub, Mesulam, & Kramer, 1981).

The neural structures underlying the receptive processing of linguistically based intonation, like those for affective intonation, are presently unclear; receptive impairments for linguistic intonation have been associated with both right (Blonder et al., 1991; Heilman et al., 1984; Pell & Baum, 1997; Weintraub et al., 1981) and left (Heilman et al., 1984; Pell & Baum, 1997) hemisphere dysfunction. None of these studies, however, has specifically examined how unilateral brain-damaged subjects use the individual acoustic cues to linguistic prosody in perception (but see Behrens, 1986; Cooper, Soares, Nicol, Michelow, & Goloskie, 1984; Ryalls, Joanette, & Feldman, 1987; Shapiro & Danly, 1985, for data on production skills).

In a recent experiment, Pell and Baum (1997) administered identification tasks of both affective- and linguistic-prosodic stimuli to LHD, RHD, and normal subjects in three conditions: a semantically ''well-formed'' condition, in which both prosodic and semantic information cued the intonational target; a ''nonsense'' condition, in which phonetically plausible but meaningless utterances were intoned to convey the prosodic target; and a ''filtered'' condition, in which the well-formed utterances were low-pass filtered to obscure the linguistic content but retain prosodic cues. In addition to the three levels at which comprehension abilities were tested, subjects were also required to make a same/different discrimination judgment about pairs of speech-filtered utterances, thereby testing for the presence of an underlying perceptual deficit in subjects' ability to decode prosodic information.

Results of the identification tasks revealed that neither LHD nor RHD subjects were impaired relative to normals in comprehending affective-prosodic stimuli, overall, but that both patient groups were impaired in identifying grammatically based intonation. Comprehension deficits, where observed, did not appear to be related to a perceptual impairment, since both patient groups were as accurate as normal subjects in discriminating prosodic patterns (Pell & Baum, 1997). However, since the stimulus pairs presented for discrimination differed with respect to all available vocal cues, it remains plausible that subjects were attending to particular acoustic cues and misperceiving or not attending to others (Van Lancker & Sidtis, 1992), and that a perceptual disturbance may indeed have contributed to their performance in identifying intonational meanings.

The primary goal of the present investigation was to follow up on the results of Pell and Baum (1997) and, following the paradigm described by Van Lancker and Sidtis (1992), explore further how brain-damaged patients comprehend discrete emotional and grammatical meanings conveyed by prosody. First, we examined the accuracy of LHD, RHD, and normal control subjects on two previously administered tasks of identifying linguistic and affective prosody in which nonsense stimuli were presented (Pell & Baum, in press). Subsequently, we investigated whether the comprehension difficulties of each clinical group were systematically influenced by particular (and potentially different) acoustic cues on the linguistic and affective tasks (Van Lancker & Sidtis, 1992).

Thus, the present analyses allowed the performance of the LHD and RHD patients reported in Pell and Baum (1997) to be assessed further to determine the acoustic basis of their comprehension of affective and linguistic prosody. Moreover, they permitted the testing of Van Lancker and Sidtis's (1992) specific hypothesis that LHD and RHD patients rely on different sets of acoustic cues in identifying emotional prosody, due to an underlying perceptual impairment for the stimuli.

METHOD

Subjects

The 29 subjects were those tested previously, as reported in Pell and Baum (1997). Ten patients with single focal lesions of the left hemisphere and resulting aphasia (9 nonfluent, 1 fluent), 9 patients with focal right-hemisphere lesions and no accompanying aphasic deficit, and 10 healthy nonneurological control subjects were examined. The presence and location of lesions for brain-damaged subjects were documented by CT scan in all but two cases, in which contralateral hemiparesis served as the diagnostic confirmation of left- or right-hemisphere damage; lesions were located predominantly in fronto- or temporoparietal regions for both groups. Testing of subjects in the two clinical groups occurred at least 3 months post-CVA, at which time patients did not have a lasting visual neglect as determined by the Bells Test (Gauthier, Dehaut, & Joanette, 1989).

All subjects were right-handed, native English speakers from the Montreal and Toronto regions who showed normal hearing sensitivities at 0.5, 1, and 2 kHz following a puretone air conduction screening. None of the participants had been diagnosed with neurologic or psychiatric illness prior to testing, apart from the single-event CVA in the case of brain-damaged subjects. Experimental groups were balanced closely for mean age and gender; Table 1 summarizes basic demographic and clinical characteristics of each group.

Stimuli

Sixty nonsensical word-strings, 30 conveying affective meanings and 30 conveying linguistic meanings (described below), were presented to subjects in a previous experiment of com-

TABLE 1
Demographic and Clinical Characteristics of the LHD, RHD, and Normal (NC) Subject Groups Tested in Pell and Baum (1997)

Group	*n*	Sex (F/M)	Age	Postonset[a]
LHD	10	6/4	63.6 (14.0)	31 (23)
RHD	9	5/4	64.7 (10.5)	15 (09)
NC	10	5/5	64.7 (7.9)	—

Note. Standard deviations are indicated in parentheses.
[a] In months.

prehension abilities (Pell & Baum, 1997); this stimulus set was used as the basis of the present investigation.

Ten ''language-like'' but semantically nonsensical utterances consisting of eight to nine syllables each were constructed by substituting syllables of semantically well-formed sentences with phonetically plausible alternatives, rendering the sentences meaningless (see Appendix). Each nonsense utterance was recorded by a female speaker using six distinct intonation patterns: angry, sad, and happy (affective context); declarative, interrogative, and imperative (linguistic context). The adequacy of the stimuli in conveying the desired emotional or linguistic meaning had been confirmed by a group of listeners (see Pell & Baum, 1997).

Several factors suggested that the nonsense stimuli condition in Pell and Baum (1997) would be most appropriate for the present analyses. The same 10 nonsense utterances were intoned to represent each affective and linguistic target meaning, thereby diminishing the effect that different items would have on the acoustic measures across categories. As well, the absence of meaningful verbal information limited the potentially distracting effect of semantic processing (Bowers et al., 1987), providing a better measure of the ability of brain-damaged subjects to attend strictly to prosodic information in speech. Finally, in comparing our comprehension task using nonsense utterances and Van Lancker and Sidtis' (1992) task using semantically neutral, natural utterances, it can be seen that the *level* of observed impairment of each subject group was comparable (see Fig. 1), suggesting that a legitimate comparison of subjects' errors across studies might be achieved.

Acoustic Analyses

Each of the 60 nonsense utterances was digitized using the BLISS speech analysis system (Mertus, 1989) at a sampling rate of 20 kHz using a 9-kHz low-pass filter. In strict accordance with the methods utilized by Van Lancker and Sidtis (1992), syllable boundaries were demarcated and the duration of each syllable within each utterance was recorded. Mean F0 and amplitude measures for each syllable were also computed. For fundamental frequency and duration, the syllable means were then used to calculate a mean value for each utterance, and the differences between adjacent syllable means were averaged to arrive at an indication of the syllable-to-syllable variability of each acoustic cue for each sentence.

For amplitude, our methods diverged somewhat from those employed by Van Lancker and Sidtis (1992). Due to slight differences in the level at which utterances were recorded and digitized, *relative* measures of the overall amplitude and syllable-to-syllable variability in amplitude were formulated for each utterance, again using the syllable means (for mean amplitude) and the syllable-to-syllable differences (for amplitude variation). Instead of averaging

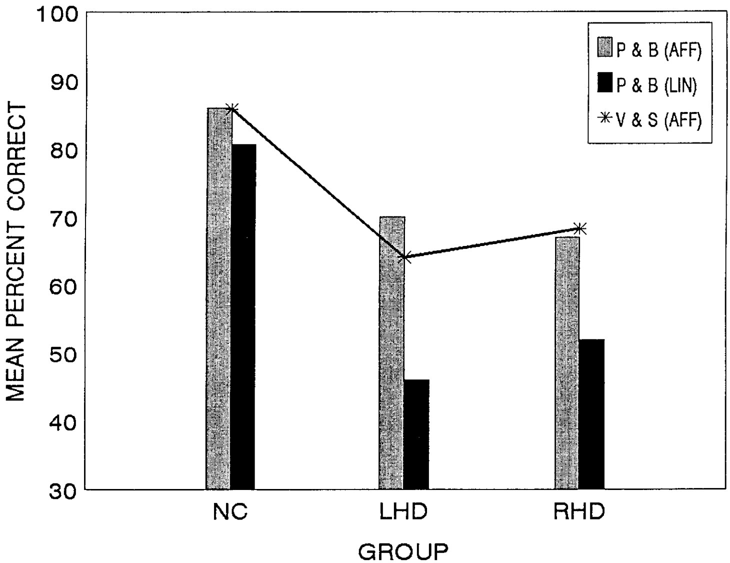

FIG. 1. Percent correct responses, by group, in identifying affective (AFF) and linguistic (LIN) prosody from nonsense utterances (Pell & Baum, 1997). Results of a task of identifying affective prosody [Van Lancker & Sidtis (V&S), 1992] are shown for comparison purposes.

these figures directly for each utterance, a ratio of the highest mean syllable amplitude (for mean amplitude) or largest difference (for amplitude variation) to the utterance mean was used in the analyses. Thus, consistent with Van Lancker and Sidtis (1992), six acoustic variables were derived to describe each of the 30 affective and 30 linguistic utterances incorporated into the discriminant analyses.

Statistical Analyses

The accuracy of the three subject groups tested in Pell and Baum (1997) in identifying the three linguistic and three affective target meanings was analyzed using two separate 3 × 3 mixed-design ANOVAs. Group membership (NC, LHD, RHD) served as the between-subjects factor in both cases, and emotion type (angry, sad, happy) and sentence type (declarative, interrogative, imperative) constituted the repeated measure in the analyses of the affective and linguistic data, respectively.

To establish in what way the emotional- and linguistic-prosodic stimuli presented to subjects on identification tasks could be distinguished acoustically, and to discern which of these acoustic cues were important in determining the pattern of error responses produced by LHD and RHD patients, the six acoustic parameters determined for each utterance were used as independent variables in performing three separate discriminant function analyses on both the linguistic and the affective data, following Van Lancker and Sidtis (1992).

The first discriminant analysis sought to differentiate the stimuli according to their *intended* emotional or linguistic meaning, using the six acoustic measures derived for each stimulus. The second and third discriminant analyses attempted to predict the *error* responses of the LHD and RHD groups, respectively, on affective and linguistic tasks, using the same acoustic data. Error analyses, as discussed in the foregoing discussion, permitted a direct test of Van

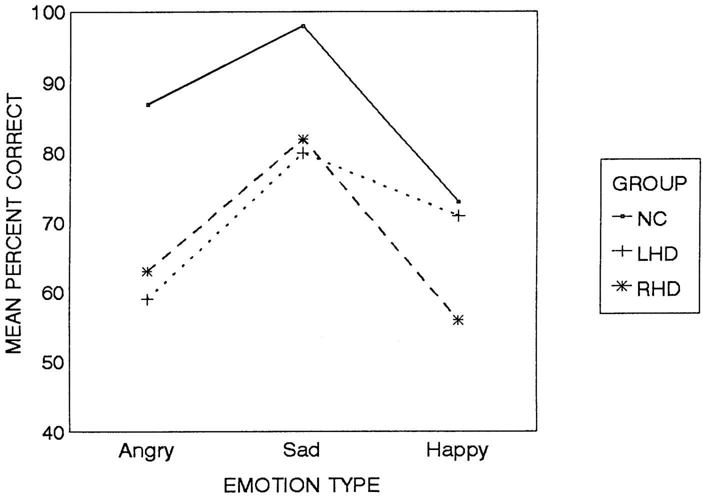

FIG. 2. Percent correct responses, by group, in identifying angry, sad, and happy sentences from nonsense stimuli.

Lancker and Sidtis' (1992) finding that the comprehension errors of LHD and RHD patients, although not significantly different in number, are derived from a systematic misuse of different acoustic cues to prosody (F0 and duration, respectively).

Discriminant analyses on patients' errors were conducted in a manner identical to that described by Van Lancker and Sidtis (1992). For each stimulus, the most frequent error was first determined. As described earlier, the stimuli were then reclassified according to that misidentification and the fully recoded set was subjected to a separate discriminant analysis for each group to determine whether a reliance on specific acoustic variables would predict their prosodic misclassifications. Thus, in the case of the error analyses, we explored the acoustic cues that may have directed LHD or RHD patients to *misinterpret* the meaning of the stimuli, possibly in a systematic manner (Van Lancker & Sidtis, 1992).

RESULTS

Comprehension Tasks

Affective stimuli. The results of a group × emotion-type ANOVA on the data collected in Pell and Baum (1997) for the affective stimuli yielded a significant main effect for emotion type [$F(2, 52) = 12.68$, $p < .001$], depicted in Fig. 2, and a marginally significant main effect for group [$F(2, 26) = 3.19$, $p = .058$]. Post hoc analyses of the emotion-type main effect using Tukey's method ($p < .05$) revealed that, overall, subjects were able to recognize sad intonation significantly better than happy intonation. Identification of angry stimuli did not significantly differ from performance on either happy or sad stimuli. The marginally significant group main effect primarily reflected the superior performance of the NC group relative to the two brain-damaged groups (LHD, RHD), who did not differ.

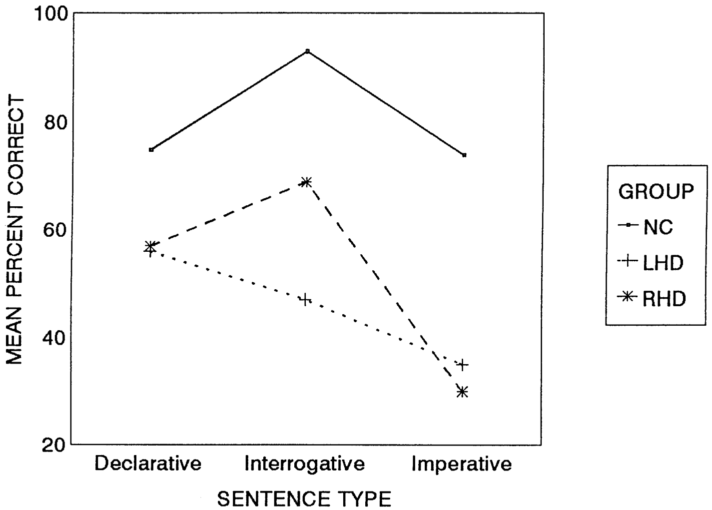

FIG. 3. Percent correct responses, by group, in identifying declarative, interrogative, and imperative sentences from nonsense stimuli.

Linguistic stimuli. A group × sentence-type ANOVA for the linguistic data (from Pell and Baum, 1997) revealed significant main effects for group [$F(2, 26) = 18.69$, $p < .001$] and sentence type [$F(2, 52) = 12.74$, $p < .001$]. In addition, a group by sentence-type interaction was found [$F(4, 52) = 2.88$, $p < .05$], as displayed in Fig. 3. Post hoc Tukey tests ($p < .05$) of this interaction revealed that the three subject groups did not differ in their ability to identify declaratives from the intonational cues, but that both LHD and RHD subjects were significantly less able than NC subjects to identify interrogatives and imperatives. Further, LHD subjects were significantly less accurate than RHD subjects in labeling interrogative intonation, but did not differ from RHD subjects in their ability to identify imperative intonation.

Acoustic and Error Analyses

Affective stimuli. The six acoustic measures obtained for the affective stimuli are provided in Table 2 according to emotion type (angry, sad, happy). To further characterize the relationship among the acoustic variables, Pearson correlations of these measures were computed; correlations were high only between mean F0 and F0 variability ($r = 0.56$). One-way ANOVAs revealed significant differences across the three emotional categories for mean F0 [$F(2, 27) = 9.82$, $p < .001$], F0 variability [$F(2, 27) = 8.11$, $p = .002$], and a marginally significant difference for mean syllable duration [$F(2, 27) = 3.33$, $p = .05$]. Tukey post hoc tests ($p < .05$) revealed that the effects related to mean F0 and F0 variability reflected differences between the sad

TABLE 2
Syllable Means (mean) and Syllable-to-Syllable Variability (var) of Each Acoustic Measure for the Three Affective Sentence Types

	F0		Duration		Amplitude	
Emotion type	Mean	Var	Mean	Var	Mean	Var
Angry	231	30	237	157	1.71	2.01
	(19)	(12)	(29)	(42)	(0.27)	(0.39)
Sad	204	13	240	164	1.83	2.26
	(8)	(5)	(27)	(39)	(0.39)	(0.52)
Happy	233	32	267	160	1.75	2.32
	(19)	(16)	(28)	(36)	(0.24)	(0.49)

Note. Fundamental frequency (F0) is presented in Hz, duration is presented in msec, and amplitude is presented as a relative measure of the maximum to mean syllable values in RMS units (standard deviations are indicated in parentheses).

stimuli relative to both the angry and happy stimuli (which did not differ), and that the effect related to mean syllable duration was accounted for by the difference between angry and happy stimuli.

To establish which of the acoustic parameters differentiated the three emotions, a discriminant analysis of the intended emotional categories presented on the comprehension task was conducted, yielding a significant canonical discriminant function [$\chi^2(12) = 27.46$, $p < .01$] accounting for 76% of the variance in the data. This function was found to be strongly related to mean F0 ($r = .70$) and F0 variability ($r = 0.64$). A second discriminant function describing 11% of the variance correlated highest with mean syllable duration ($r = 0.65$) but was not statistically significant [$\chi^2(5) = 6.23$, $p > .28$]. Overall, the discriminant function correctly predicted 24 of the 30 intended emotions, for a success rate of 80%.

Figure 4 plots the 30 affective stimuli according to their discriminant scores on the two functions. It can be seen that the sad stimuli separate relatively well from the angry and happy stimuli on the basis of Function 1, reinforcing previous assertions that sorrow is conveyed with a relatively low F0 and little variability in vocal pitch (see Scherer, 1986, for a review). Angry and happy stimuli separate less well; the discriminant function was particularly inefficient at predicting the 10 angry stimuli, classifying 2 of these utterances as sad, and 3 as happy (error rate = 0.5 for angry stimuli, compared to 0.1 for happy stimuli, and 0 for sad stimuli). As may be noted from Fig. 4, there is somewhat greater variability in the vocal parameters that are used to convey anger and joy when compared to sorrow.

As previously described, discriminant analyses based on subjects' errors were then conducted independently for each patient group; these analyses utilized the data recoded according to the most frequent misidentification. As detailed above, the discriminant analyses aimed to reveal whether the

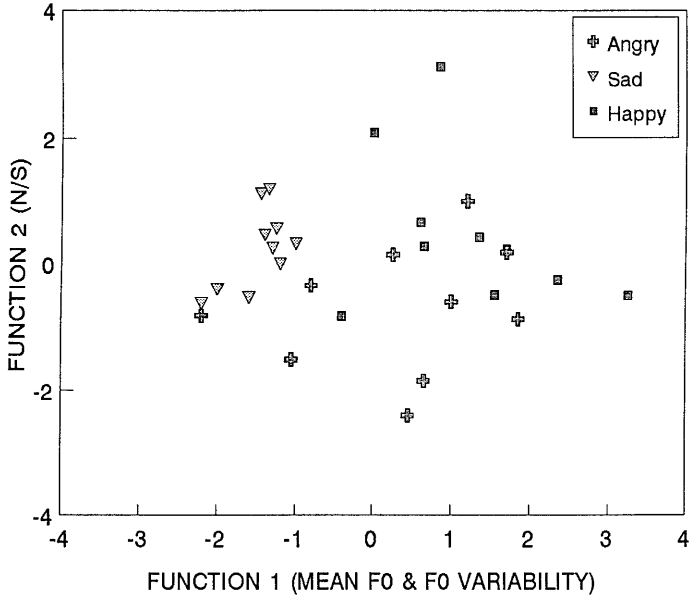

FIG. 4. Results of a discriminant analysis on the intended affective categories used in Pell and Baum (1997). Only Function 1, highly correlated with mean F0 and F0 variability, was statistically significant.

LHD and RHD patients' comprehension errors were significantly influenced by specific acoustic cues to the emotional meanings, as reported by Van Lancker and Sidtis (1992). Looking at the LHD subjects' errors, 4 of the 30 stimuli resulted in two equally frequent misclassifications (ties), and 3 other stimuli resulted in no errors at all. For the RHD group, two ties and 3 stimuli for which there were no errors occurred. Because these items could not be appropriately reclassified, they were eliminated from the analysis of each group's errors.

Additional stimuli (4 for the LHD group, 7 for the RHD group) for which only a single error response was observed were excluded from the analysis of each group; these errors are likely to have occurred by chance and thus would not indicate a systematic tendency toward one or another error category. In total, therefore, 19 stimuli were incorporated into the discriminant analysis of the LHD subjects' errors, and 18 stimuli were included in the analysis of the RHD subjects' errors. The most frequent error responses of the remaining stimuli accounted for 86 and 78% of the total errors of the LHD and RHD groups, respectively.

The discriminant analysis of the LHD subjects' errors was successful in predicting 74% of their affective misclassifications, but did not yield a statistically significant discriminant function [$\chi^2(12) = 10.52$, $p = .57$; $\chi^2(5) =$

TABLE 3
Syllable Means (mean) and Syllable-to-Syllable Variability (var) of Each Acoustic Measure for the Three Linguistic Sentence Types

	F0		Duration		Amplitude	
Sentence type	Mean	Var	Mean	Var	Mean	Var
Declarative	219	20	193	122	1.74	2.28
	(9)	(6)	(67)	(32)	(0.25)	(0.46)
Interrogative	256	34	198	105	1.57	2.37
	(12)	(16)	(25)	(25)	(0.24)	(0.52)
Imperative	256	31	192	90	1.82	2.34
	(18)	(13)	(16)	(40)	(0.24)	(0.69)

Note. Fundamental frequency (F0) is presented in Hz, duration is presented in msec, and amplitude is presented as a relative measure of the amplitude peak over the mean in RMS units (standard deviations are indicated in parentheses).

4.16, $p = .52$]. For the RHD group as well, neither the first [$\chi^2(12) = 9.83$, $p = .63$] nor the second [$\chi^2(5) = 1.87$, $p = .86$] discriminant function was significant; the most frequent errors for the RHD group were predicted less reliably (67% success rate) than for the LHD group.

Linguistic stimuli. Table 3 summarizes the six acoustic measures derived for each of the three sentence types (declarative, interrogative, imperative) presented on the comprehension task of linguistic intonation. Correlations between the mean and variability measures of duration ($r = 0.53$) as well as fundamental frequency ($r = .37$) were noted for the linguistic stimuli. One-way ANOVAs for each acoustic variable demonstrated that the three linguistic categories differed significantly only with respect to mean F0 [$F(2, 27) = 24.49$, $p < .001$] and F0 variability [$F(2, 27) = 3.50$, $p < .05$]. Post hoc analyses of these effects using Tukey's method ($p < .05$) indicated that for mean F0, declaratives differed significantly from interrogatives and imperatives (which did not differ), and that declaratives further differed from interrogatives with respect to F0 variability.

A discriminant analysis on the intended sentence types yielded a significant canonical discriminant function [$\chi^2(12) = 34.55$, $p < .01$] accounting for 83% of the variance in the data; this function was highly correlated with mean F0 ($r = .91$). A second discriminant function, describing 8% of the variance and negatively correlated with mean amplitude ($r = -0.82$), did not reach significance [$\chi^2(5) = 5.99$, $p = .30$]. The discriminant analysis correctly predicted 25 of the 30 intended linguistic categories, for a success rate of 83%.

The 30 linguistic-prosodic stimuli are plotted in Fig. 5 with respect to their discriminant scores on the two functions. It can be seen that declaratives separate relatively well from interrogatives and imperatives based on the first function, indicating that declarative utterances are generally expressed with

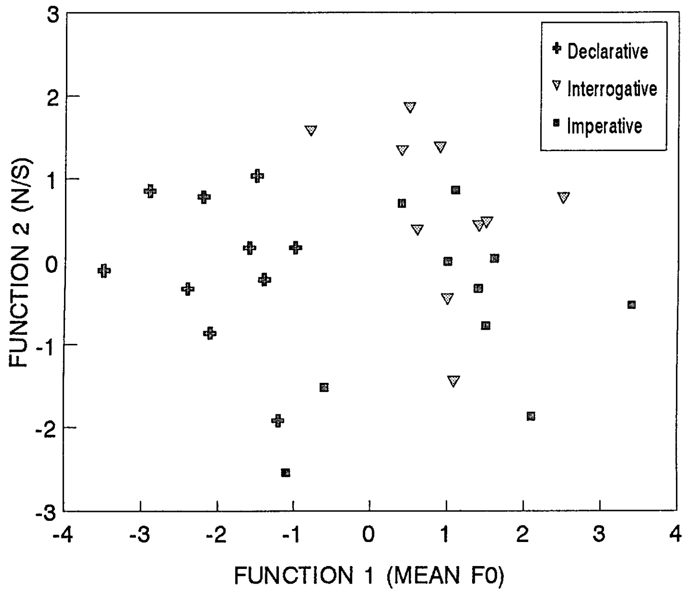

FIG. 5. Results of a discriminant analysis on the intended linguistic categories used in Pell and Baum (1997). Only Function 1, highly correlated with mean F0, was statistically significant.

a lower mean fundamental frequency than imperative or interrogative utterances. There was considerable overlap between interrogatives and imperatives on the basis of Function 1 (mean F0); indeed, the error rate in predicting interrogatives and imperatives from this analysis based on the acoustic characteristics was 0.20 and 0.30, respectively, whereas all declaratives were correctly predicted (error rate = 0).

For the error analyses in the linguistic condition, 3 of the 30 stimuli were excluded for the LHD group due to two equally frequent error classifications, leaving 27 items to incorporate into the analysis. For the RHD group, 6 stimuli resulted in ties and 2 resulted in only a single error response; therefore, only 22 items were considered in the analysis of the RHD subjects' errors. For the remaining stimuli, the most frequent error responses of the LHD and RHD groups accounted for 74% and 76% of their total errors, respectively.

The error analysis of the LHD group gave rise to a significant discriminant function [$\chi^2(12) = 25.87$, $p = .01$] carrying 76% of the variance and highly related to mean F0 ($r = 0.76$). A second discriminant function was nonsignificant [$\chi^2(5) = 7.21$, $p > .20$]. The overall success rate of the analysis was 85%. A similar finding emerged for the analysis of errors made by RHD subjects, in that only one significant discriminant function (79% of variance) correlated strongly with mean F0 ($r = 0.84$) emerged [$\chi^2(12) = 21.68$, $p <$

.05]. Again, the second canonical function for this analysis did not reach statistical significance [$\chi^2(5) = 5.28, p = .38$]. Correct classification of the RHD group's errors was predicted in 86% of the cases.

DISCUSSION

The present study had two primary objectives. The first goal was to test the hypothesis that left and right unilateral brain-damaged subjects rely on different acoustic cues in the comprehension of affective prosody (Van Lancker and Sidtis, 1992). Related to this objective, the second goal was to further examine whether the comprehension difficulties of the patients reported in Pell and Baum (1997) were related to a defect in *perceiving* the prosodic features of the linguistic or affective stimuli (Bowers et al., 1987; Robin et al., 1990; Van Lancker & Sidtis, 1992). An additional outcome of the investigation are data on the acoustic cues that serve to differentiate the stimulus types.

Acoustic and discriminant analyses of the affective stimuli demonstrated that fundamental frequency and its variation were of primary importance in distinguishing the emotional utterances presented in Pell and Baum (1997), although F0 cues alone did not specifically differentiate the angry and happy stimuli. The finding that F0 was of primary importance in distinguishing affective meanings is consistent with data reported by Van Lancker and Sidtis (1992) for their stimulus set and is in general accord with previous acoustic descriptions of emotional prosody (Cosmides, 1983; Fairbanks & Pronovost, 1939; Lieberman & Michaels, 1962; Scherer, 1986; Williams & Stevens, 1972).

However, the analysis of the errors made by LHD and RHD subjects on the affective task failed to demonstrate systematic differences across the groups in the use of F0, duration, or amplitude in judging the emotional meaning of the stimuli. The discriminant analyses performed on the errors of each clinical group did not reach statistical significance and were therefore unsuccessful in establishing distinct perceptual bases for subjects' errors through the isolation of certain acoustic variables. Thus, the present findings stand in contrast to Van Lancker and Sidtis' (1992) report that LHD and RHD patients, who demonstrated comparable deficits in identifying affective-prosodic stimuli, were impaired due to the ''misuse'' of different auditory cues to the stimuli—F0 variability and syllable duration variability for the LHD and RHD subjects, respectively.

In extending Van Lancker and Sidtis' (1992) paradigm to a stimulus condition exploring linguistic prosody, we were similarly unable to discern differences between left- and right-hemisphere-damaged subjects in the use of the six acoustic measures; the discriminant analysis on the intended linguistic categories, as well as those on the comprehension errors of each patient group, consistently pointed to the significance of mean F0 in distinguishing the three sentence types. These results are not surprising given the rise versus fall in F0 that signals the interrogative/declarative distinction in English. It is also not surprising that imperative stimuli with (highly probable) increased stress on certain words had higher mean F0 than declarative sentences.

Although there is no direct precedent to our analyses of the errors in the linguistic context (i.e., Van Lancker & Sidtis, 1992, did not examine linguistic prosody), the implications of these findings are important in that they reaffirm that the left- and right-brain-damaged patients did not rely on distinct sets of acoustic features in comprehending prosody for either affective or linguistic stimuli. Moreover, the present findings do not support claims that the processing of temporal and spectral parameters of speech prosody are dissociable in the brain (Robin et al., 1990); nevertheless, nor do the results necessarily refute such a hypothesis.

Although rigorous attempts were undertaken in the present study to replicate the methods set out by Van Lancker and Sidtis (1992), remaining methodological differences between the two studies may have influenced the different patterns of results obtained. For example, it is well known that there is considerable variability in the way discrete emotions can be expressed vocally (Cosmides, 1983; Scherer, 1986). In the current investigation, the use of a larger number of exemplars to represent each emotional intonation (i.e., 10 vs. 4) probably resulted in greater overlap in the acoustic properties of our three emotional categories relative to the four categories employed by Van Lancker and Sidtis (1992). This increased variability within our stimulus set—although clearly an important reality of speech production—may have contributed to less predictable error responses based on the six acoustic cues utilized.

A second factor that may in part account for the differences across the studies is the number of subjects who participated in the original identification tasks. In the present experiment, the affective misclassifications of 10 LHD and 9 RHD patients were incorporated into the discriminant analysis for each group, a far smaller number of errors than would have contributed to Van Lancker and Sidtis' (1992) findings, given their 24 LHD and 13 RHD subjects. The lower number of subjects, and therefore *error observations*, in the present study may have limited our ability to detect a pattern in the error data, if present.

Finally, with respect to the hypothesis of separable and differentially lateralized processing of cues, the comprehension of affective prosody by LHD and RHD patients may indeed be influenced by specific and unique acoustic cues (Van Lancker & Sidtis, 1992), but not those considered in the present analyses. Many additional measures, including the acoustic correlates of voice quality (e.g., F0 perturbation, differences in spectral energy distribution), the overall range of F0 and/or amplitude, the rate of F0 and/or amplitude change, rate of articulation, etc., have been shown to be implicated in the vocal expression of emotion (see Scherer, 1989, for an overview); one or a combination of these additional parameters may have been used by LHD or RHD patients in interpreting the affective meaning of utterances. However, this possibility would not in any way undermine our failure to replicate differential sensitivity in the LHD and RHD subjects to the acoustic cues tested by Van Lancker and Sidtis (1992).

As reported above, the discriminant analysis performed on the three intended emotional categories revealed that mean F0 and its variation best differentiated the 30 stimuli. The plot of these stimuli according to the scores on the two canonical functions, however, revealed that only sad stimuli separated well from the other emotional utterances according to the F0 measures; considerable overlap in the pitch characteristics of the angry and happy stimuli was evident. On the hypothesis that subjects were indeed attending to F0 information in their perceptual analysis of the emotional stimuli, one would anticipate high accuracy in identifying sad intonation, but more ambiguity with respect to angry and happy intonation, resulting in lower accuracy in identifying these two emotions. In fact, the performance of all three subject groups (LHD, RHD, NC) closely corresponded to the predicted pattern; sad stimuli were identified most reliably by all three subject groups, whereas angry and happy utterances were less efficiently labeled in all cases.

Although the present findings did not unambiguously indicate whether or not LHD and RHD patients were using fundamental frequency in identifying emotional meanings, given the importance of F0 in differentiating the stimuli and the relatively high accuracy of the two patient groups on the nonsense task (Pell & Baum, 1997, reported the accuracy of the LHD and RHD groups at 70% and 67% overall, where chance level was 33%), it is highly probable that the brain-damaged patients retained at least a partial capacity to analyze the F0 characteristics of the stimuli. As noted earlier, this would not preclude the subjects' use of other (unexplored) acoustic cues in making their decisions.

For the linguistic data, discriminant analyses on the intended sentence-type groupings revealed that declaratives separated well from interrogatives and imperatives in terms of mean F0. However, it is essential to point out that other important differences across the linguistic stimuli were probably quite salient to these subjects. In particular, two distinct contours, those having a terminal rise in F0 (interrogatives) and those exhibiting a terminal decline in F0 (declaratives, imperatives), differentiated the set of linguistic stimuli. Although the present acoustic descriptions of the stimuli did not separately account for this categorical distinction marked by the rise or fall of the F0 terminal, these cues are clearly an important factor in distinguishing linguistic-prosodic meanings (Bolinger, 1978; Fry, 1970; Ladd et al., 1985).

Indeed, the pattern of performance of our control group, as well as that of the RHD patients, shows precisely this sensitivity to the shape of the prosodic contour in judging the linguistic stimuli; both subject groups displayed superior recognition of interrogatives relative to declaratives and imperatives. In contrast, the LHD subjects demonstrated little sensitivity to the rise or fall of the F0 contours in judging the stimuli, commiting significantly more errors in identifying interrogatives than both the RHD and normal subjects and showing a general bias toward declaratives in their responses. Curiously, this pattern of performance corresponds to the salience of the linguistic stimuli with respect to the overall measure of mean F0 employed in the present analyses (review Fig. 5, above).

The data indicate, therefore, that LHD subjects were less able than normal or RHD subjects to assess the linguistically defined categorical properties of prosodic stimuli (i.e., the terminal rise/fall of the F0 contour) in judging their meaning; moreover, trends in the data suggest that LHD patients may have relied on the (less informative) *continuous* aspects of F0 cues in processing these stimuli. Impaired knowledge of linguistic-prosodic representations, or a deficit in the ability to associate these representations with the acoustic input, may therefore underlie comprehension deficits previously attributed to LHD subjects for linguistic prosody (Pell & Baum, 1997). Our conclusion that the LHD patients' deficits were specific to the linguistic structure of suprasegmental cues is consistent with data reported in a similar receptive study comparing linguistic and affective prosody (Heilman et al., 1984), and is in general accord with a left-hemisphere superiority in the processing of propositionally related stimuli.

Certainly, receptive deficits for linguistic or affective prosody (such as those described herein) are not a uniform feature of focal brain damage, but likely differ depending on the locus and extent of right or left intrahemispheric insult. Given the current lack of consensus as to how (and indeed if) prosodic stimuli are lateralized on receptive tasks (see Introduction), it is of little surprise that the neuroanatomical correlates of linguistic and affective prosody *within* the cerebral hemispheres remain elusive; prior research does, however, indicate a potential association between prosodic comprehension disturbances and lesions localized to right and/or left temporoparietal regions of the cortex (Blonder et al., 1991; Heilman et al., 1975; Ross, 1981; Schlanger et al., 1976; Tucker et al., 1977; Van Lancker & Sidtis, 1992, 1993). As lesion site varied somewhat within our clinical groups, the present data neither substantiate nor disconfirm such a link between temporoparietal lesions and impaired comprehension of prosody, although it is noteworthy that approximately half of the subjects in each of our patient groups suffered damage to closely adjacent regions (temporo- and/or frontoparietal) as documented by CT scan (Pell & Baum, 1997).

However, contradictory evidence, including ''negative'' cases of patients with temporoparietal damage and intact prosodic comprehension (Lebrun et al., 1985) and patients demonstrating dysprosodies following lesions distributed in various regions of the two hemispheres (Cancelliere & Kertesz, 1990) will need to be reconciled if a strong link between discrete temporoparietal lesions and receptive impairments for prosody is to be established. These findings will similarly need to be accounted for if models that place the emotional components of language (e.g., ''sensory'' or ''motor'' prosodic capabilities) in right-hemisphere regions homologous to those that subserve propositional language in the left hemisphere are to be accepted (Ross, 1981). Cancelliere and Kertesz's (1990) observation that receptive dysprosodies occurred most frequently following *subcortical* damage involving the basal ganglia may provide an alternate means by which to explore the neural substrates of prosody; indeed, this line of inquiry may eventually help identify neural pathways committed specifically to the receptive control of suprasegmental cues (Blonder, Gur, & Gur, 1989).

In summary, despite differences between left- and right-brain-damaged patients in decoding linguistic-prosodic stimuli on experimental tasks, it must be reiterated that our data do not confirm reports that unilateral left- and right-hemisphere lesions produce a systematic misuse of different *acoustic* cues to either affective or linguistic prosody (Van Lancker & Sidtis, 1992). Future investigations will need to address a larger range of acoustic variables, and explore the influence of both continuous and categorical aspects of suprasegmental information, if we are to illuminate how brain-damaged patients perceive the acoustic cues to affective and linguistic prosody. The highly interactive relationship between the linguistic and emotional aspects of prosodic structure in natural speech will also require systematic exploration if we are to understand the relative contribution of each hemisphere in the processing of sentence prosody.

APPENDIX

Nonsense Stimuli

1. Ra hont kawtee thashem adnice.
2. Geer hab ode kwintely tozing.
3. Ya zume vaught chestin fondi heidz.
4. Roo shaw chestily wah kumet.
5. Suh feckter egzullin tuh boshen.
6. Jodah eezeth aram pazing.
7. A hootlie gag nee fabiluck.
8. Shayaluh vortiful hack bah rotes.
9. Kwa pow uzes pawjist hapule.
10. Me sha neenal ploe duh kistore.

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