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SPEECH MINUS SPECTRUM EQUALS TIME
-- OR WHAT THE LEFT HEMISPHERE IS FOR

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It is known to speech scientists that the study of speech, whether from an acoustic, perceptual, or productive standpoint, cannot be complete unless both the temporal and the spectral dimensions are taken into consideration. However, does this mean that subtracting from speech its spectral representation would leave us with its temporal representation? Obviously, from the physical standpoint, such a subtraction is meaningless. Nevertheless, the experiments described below tend to sway us toward the conclusion that, from the point of view of the brain mechanisms specializing in speech perception, the equation "speech-spectrum = time" may acquire a certain significance. What these experiments demonstrate is that the auditory mechanisms responsible for speech perception may be separated into two distinct components: one that processes the speech stimulus in the spectral, and one that processes it in the temporal domain. Moreover, these experiments also strongly suggest that, whereas spectral processing is essentially complete already at some subcortical level, the most likely site for temporal processing of the speech signal lies somewhere in the left cortical hemisphere. The method that enables us to reach these conclusions is that of simultaneous dichotic listening.

Two speech sounds presented simultaneously one to each ear are generally found to interfere with each other's perception. This perceptual interference is clearly manifest: while the sound can be identified perfectly (or almost perfectly) when it is presented separately to each ear, the simultaneous presence of a different speech sound in the other ear greatly impairs the recognition of either stimulus. Often, the observer cannot correctly identify more than 40-60 per cent of the stimuli. However, the accuracy of the perception in the two ears is seldom identical. Kimura (1961) was the first to report that, when using dichotically presented digits, the great majority (about 80 percent) of her right-handed subjects identified the stimulus coming to their right ear more often correctly than the one coming to their left ear. This perceptual asymmetry has been named right-ear advantage (REA) and has been interpreted to reflect a left-hemishpheric dominance for the processing of speech sounds. This interpretation, though only inferential, is based on anatomical and physiological evidence showing that the major portion of afferent fibers originating in the cochlea innervate, after multiple synapses, contralateral cortical areas (Rosenzweig, 1951; Hall and Goldstein, 1968). However, such a cross-innervation is by no means absolute: in addition to some non-crossing afferent fibers that originate in the cochlear nucleus, there are several subcortical (olivary, collicular) and cortical (the cerebral commissures, mainly the corpus callosum) sites at which the two sides of the system are connected (Whitfield, 1967). The fact that the REA for speech sounds is relatively small (typically a 5-15 per cent difference betwen right- and left-ear recognition scores in normal subjects) is generally attributed to the crossing of auditory information through any one or several of these connections, especially through the corpus callosum. It has been reported (Milner et al., 1968; Sparks and Geschwind, 1968) that split-brain subjects (i.e., patients whose corpus callosum, and often the anterior commissure as well, has been surgically sectioned) show a 100 per cent REA. Thus, while the proof of left-hemispheric dominance for speech perception in normals is at most weak, strong support for this functional asymmetry derives from clinical observations. The most direct evidence is provided by studies on left temporal-lobe damaged patients (Milner, 1967) and on normals whose one hemisphere has become temporarily dysfunctional due to unilateral intracarotid drug (amytal) injection (Wada and Rasmussen, 1960).

The question arises: what does the essence of REA and, by conjecture, of left-hemispheric dominance for speech consist of? Early experiments on this topic uncovered a reliable (albeit small) REA for various pairs of dichotic words and nonsense syllables (Kimura, 1961, 1967). However, because of the ready availability of synthetic speech material and the better stimulus control that it offers, there has been an ever increasing number of studies dealing with ear advantage for various phonetic features in dichotically presented speech. An overview of these studies reveals that appreciable REA can be found only for consonants (Shankweiler and Studdert-Kennedy, 1967; Studdert-Kennedy and Shankweiler, 1970; Haggard and Parkinson, 1971). Initial consonants in CV or CVC syllables exhibit a larger REA than do final consonants (Studdert-Kennedy and Shankweiler, 1970). In initial stop consonants, it is the feature of voicing that produces a greater REA, closely followed by the feature of place-of-articulation ([bilabial], [coronal], [velar]), though the two features combined have been seen to result in an increased ear difference (Shankweiler and Studdert-Kennedy, 1967). Initial fricatives (Darwin, 1975), as well as semivowels and laterals (Haggard, 1971) also produce a REA. On the other hand, neither steady-state vowels (Shankweiler and Studdert-Kennedy, 1967; Haggard and Parkinson, 1971) nor isolated fricative sounds (Darwin, 1975) yield any reliable ear advantage, although vowels placed in the context of a CVC syllable, again, tend to favor the right ear (Weiss and House, 1973). It appears, therefore, that the lateral asymmetry for the perception of speech sounds is essentially related to acoustic features characteristic to consonants -- i.e., to time-varying speech signals.

The role of the left hemisphere in the processing of auditory temporal information is supported by a class of studies in which the stimuli were not speech sounds. Also with regard to the perception of these special non-speech sounds, direct evidence for hemispheric dominance is provided by subjects with temporal-lobe pathologies. For example, it has been shown that, in left temporal-lobe damaged patients, perception of the temporal order of two sounds (tones or strings of speech-like sounds) is seriously impaired (Efron, 1963; Swisher and Hirsh, 1972; Lackner and Teuber, 1978). Another study on similar patients demonstrated a certain impairment of the temporal fusion threshold (i.e., temporal resolution) of two dichotic clicks (Lackner and Teuber, 1973).

Experiments on normal subjects, using certain specific types of dichotic non-speech stimuli, underline the same conclusion. Thus, a REA has been found for the recognition of dichotic Morse-code signals (Papcun et al., 1973) as well as for that of dichotic tone sequences having rapid frequency transitions (Halperin et al., 1973).

In sum, it is therefore reasonable to conclude that, in normal subjects, the right ear becomes superior to the left in the perception of dichotically presented (i.e., competing) speech as well as non-speech sounds, provided that the relevant dimension is some temporal aspect of the stimulus.

There is, however, also another kind of ear asymmetry: one that has been observed time and again to accompany the perception of non-speech stimuli. Parallel to her studies on laterality effects in the perception of dichotic speech sounds, Kimura (1964) also investigated ear superiority for the perception of musical stimuli. Actually, she observed a left-ear advantage for such sounds and concluded that the right hemisphere was specialized in the processing of non-speech sounds. The idea of such a dichotomy of hemispheric specialization, however, has been challenged by other workers. One series of experiments (Gordon, 1970) showed that among dichotic tests involving the principal elements of music (melody, harmony, rhythm) only dichotic harmonies (i.e., chords) yielded left-ear advantage. Another study (Bever and Chiarello, 1974) showed that musically skilled listeners were more successful recognizing melodies with their right than with their left ear. However, even this finding was questioned by another experiment (Divenyi and Danner, 1974) which demonstrated that, with sufficient training, any ear difference in the recognition of monaurally presented melodic fragments disappear. Thus, the view that the left hemisphere specializes in speech and language processing, whereas the right in the processing of music and other non-speech sounds, seems to be ill-supported by experimental evidence.

The difference between tone sequences lies in their spectral composition, and so does the difference between two vowels, as well. We have seen that, when presented simultaneously in the two ears, neither melodies nor vowels will reveal any consistent ear advantage. Could the lack of ear superiority in the perception of dichotic vowels and dichotic tone sequences have the same cause, namely, spectral rather than temporal differences between the stimuli? A plausible answer to this question may have been offered by a series studies on a special type of ear asymmetry. This ear asymmetry may be observed when two tones close in frequency (within approximately one Critical Band, see Zwicker et al., 1957) are simultaneously presented, one to each ear. For almost every listener, the two tones fuse into a single percept having a single pitch which is dominated (to a greater or lesser degree) by the tone presented either to the right or to the left ear (Efron and Yund, 1974, 1976). Actually, only very few individuals experience a perfectly balanced dichotic pitch. Contrary to the 4:1 proportion of subjects exhibiting a REA for dichotic speech sounds, there are about as many right ear dominant as left ear dominant listeners with regard to the pitch of these dichotic complexes. This ear asymmetry has been called ear dominance for pitch (ED). ED has been found to be uncorrelated with either handedness or the ear advantage observed for speech sounds (Yund and Efron, 1975). What has been concluded from these studies is that ED is to be regarded as a consequence of an asymmetry in the processing of spectral information and is likely to be produced by asymmetries in mechanisms located at subcortical levels -- thus different from the sources thought to be responsible for the REA observed for either speech or time-varying non-speech signals. One of these asymmetries may consist of a difference in the sharpness of frequency selectivity (i.e., the tuning curves) in the two ears: the ear with a better frequency resolution will be the dominant one (Divenyi et al., 1977). ED for the relative salience of the two components that form the pitch of a dichotic two-tone complex is so strong that the pitch of the tone coming into the dominant ear will dominate that of the whole complex, even when its intensity is reduced (with respect to the intensity of the tone coming into the non-dominant ear) by sometimes as much as 40 dB. This phenomenon has been called intensity independence (Efron and Yund, 1976); it refers to the rather curious illusion that the dichotic sound may be clearly lateralized toward the non-dominant ear (i.e., the ear receiving the more intense tone), while the pitch of the sound is clearly that of the (less intense) tone coming into the dominant ear. However, the phenomenon exists only as long as the percept of the two tones is fused: when the two dichotic tones acquire two distinct pitches, due to an increased frequency separation or some other physical factor, both ED and intensity independence disappear.

There are two suggestions that follow from these experiments. Firstly, the approximately equal proportion of listeners either left- or right-ear dominant for two dichotic tones indicates that ED for spectral information is an idiosyncratic variable, too important to ignore. Thus, there are two quite possible explanations for the lack of any consistent ear advantage observed for either tone sequences or vowels: (i) Data of left-ear and right-ear dominant subjects have been customarily averaged rather than treated separately. (ii) Stimuli which either do produce binaural fusion (and which, thereby, allow ED to transpire) and stimuli which do not produce such a fusion (and which, thereby, permit the subject to selectively attend to the stimulus in either ear) have been indiscriminately mixed in most dichotic vowel and tone sequence experiments. The second suggestion, however, is most important from the linguistic point of view, for it concerns consequences of ED for *spectrally-bound* phonetic features. Because of the very nature of speech sounds, all phonetic and phonological features differ in some spectral characteristic. From the perceptual point of view, spectral processing is of primary importance for several classes of these features, e.g., vowels, fricatives, or even stop consonants. If a listener's natural ear dominance for spectrum extends to spectrally-bound phonetic features as well, then any ear advantage observed for dichotic speech sounds may be contaminated by ED. Thus, in subjects having right ED for spectral information, a REA for speech sounds is expected to be confounded with their right ED. Conversely, in subjects who are left-ear dominant for tones, any REA for speech sounds must be the consequence of other, possibly time-related asymmetry. Therefore, adequate solution to the problem of ear advantage for dichotic speech sounds can be found *only* if, in some way, ear dominance for spectral information could be dissociated from any genuinely speech-related ear asymmetry. The objective of the experiment reported below was to attempt to isolate any spectrum-bound ear asymmetry that may be present in the ear advantage for the perception of dichotic speech sounds.

Obviously, a dissociation of the ear superiority for spectral information processing from REA for speech sounds would be impossible in subjects right-ear dominant for spectrum. Thus, the key question of the experiment was whether, and in what conditions, subjects left-ear dominant for dichotic tones would display a REA. Accordingly, the experiment consisted of examining the ear advantage in such subjects for a variety of dichotically presented speech sounds. However, the paradigm departed from was the one most frequently employed in studies on the dichotic perception of speech, in that it required the subjects to *discriminate* dichotic sounds, rather than to recognize the left and/or right components in them. Therefore, this paradigm was quite simple and, in addition, had been previously proven to be a highly sensitive indicator of ear asymmetry for the pitch of dichotic tones (Efron and Yund, 1976). The paradigm, illustrated in Fig. 1, was a version of the standard Two-Alternative Forced-Choice (2AFC) method. In any given block of trials, the stimulus consisted of two monaurally discriminable sounds, "A" and "B". In half of the trials (at random), the right ear was presented with sound "A" followed (after a 500-msec interval) by sound "B" and, simultaneously, the left ear with sound "B" followed by sound "A". In the other half of the trials the order of presentation was reversed. The subjects' task was to indicate (by pressing one of two labelled keys) whether the dichotic succession they heard sounded more like "A"-"B" or "B"-"A". When the intensities of the two sounds are approximately equal, the two dichotic complexes will sound identical *only for the subject* who has *no* ear dominance for the particular stimulus property in which sounds "A" and "B"

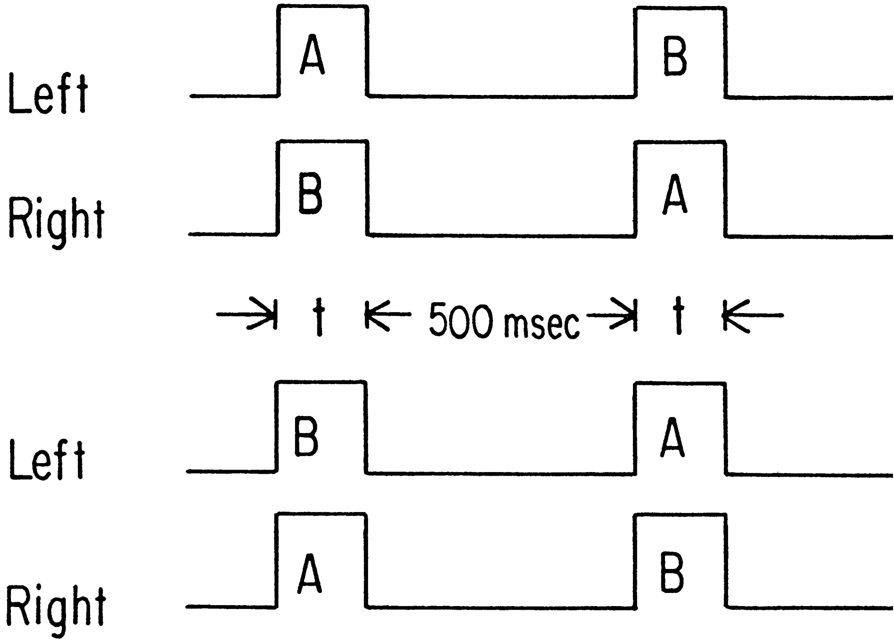

Figure 1. Schematic diagram of the dichotic stimulus pattern. "A" and "B" are two sounds with duration t (generally 80-110) msec. In each block of trials, sounds "A" and "B" are constant. At any given trial, the two left-right arrangements of the sequence "A-B" and "B-A" (upper and lower halves of the diagram) could appear with equal probability. The subject's response follows each presentation of the dichotic sequence without time constraint. His task is to indicate whether the perceived sequence sounded more like "A-B" or "B-A".

differ: for this subject, the task will be impossible and he will respond at a chance level. On the other hand, when one of the ears is dominant, the subject will be likely to report the stimulus succession presented to that ear <u>more often</u> than that presented to the other. The degree of his ear dominance for a given pair of sounds A and B thus will be reflected by the proportion of his responses corresponding to the stimulus succession in, say, his left ear. According to such a scoring system, a 100-per cent score will signify complete left ear dominance, a zero per cent score complete right ear dominance, and a 50-per cent score no ear dominance at all, with respect to the given pair of sounds A and B in question.

In the experiment, first a group of subjects was screened and, among them, five were selected who displayed a moderate-to-strong left ED for tones. More specifically, the ED scores of these subjects (see the above schema) corresponded to the stimulus succession in the left ear 88 to 100 per cent of the time, when sounds A and B were 100-msec bursts of pure tones with respective frequencies of 1650 and 1750 Hz. In addition, one subject with a moderately strong right ED (18 % left ear and, consequently, 82% right ear responses) was also included as a control. ED scores of the six subjects for the pitch of these two tones presented dichotically is shown In Table 1 (Column 1). In Column 2 of the same table the six subjects' ED scores are presented for a pair of 100-msec single-formant pseudo-vowels, i.e, synthesized periodic sounds produced by exciting a resonator tuned to either 1650-Hz or 1750-Hz (respectively) with a glottal-type waveform. It appears that each subject acquired an ED for this latter pair of sounds toward the same side as that for the pure tones. Next, the same subjects were tested for their ED with regard to five pairs of speech sounds. Each pair of sounds, with one exception, differed in only one phonetic feature. They included two CV pairs and three pairs of steady-state vowels or vowel-like sounds. The CV's were /ga/-/ka/ (differing only in the feature of voicing, i.e., VOT) and /ba/-/ga/ (differing in the feature of place of articulation, i.e., plosive burst spectrum and formant transition trajectories). The vowel pairs were /I/ with a regular and with a high (+140-Hz) first formant (differing in the acoustic parameter most important for the distinction of tongue height), /I/ with a regular and with a low (-400-Hz) second formant (differing in the acoustic parameter most relevant for the distinction of front-back tongue position), and the pair /I/-/ae/ (differing in both of these features). Acoustic parameters of the CV's closely approximated those produced at the Haskins Laboratories and used in the great majority of dichotic speech experiments, whereas the vowels followed the parameters given in the classical study of Peterson and Barney (1952) for a male speaker. The stimuli were synthesized on a laboratory computer, using a digital version of the Haskins Laboratories parallel-resonance analog speech synthesizer (developed by A.M. Engebretson and S. Garfield at Central Institute for the Deaf, St. Louis). The parameters for all dichotic sound pairs were selected such that they produced a strong binaural fusion, in order to avoid the possibility of the subject selectively attending to the stimulus in either ear. In our stimuli, binaural fusion was facilitated by keeping constant the intonation pattern (i.e., the F0 contour), the time envelope contour, and (in the CV's) the transition durations and the target vowel. The dichotic sounds were presented at either 80 or 110 msec duration. Such a short duration was chosen with the aim of giving greater emphasis to the initial consonants in the CV syllables.

Results of the experiment are displayed in Columns 3-8 of Table 1. One may see that the right-ear dominant subject (CB) displayed a REA for all speech sound pairs. Subject PM represents the other extreme: she exhibited a left-ear advantage for all pairs of speech sounds and thus falls in the same category as 20 per cent of right-handed individuals who have no REA for speech (Kimura, 1961). Subjects AG, SP, and JW remained left-ear dominant for vowels and vowel-like sounds, as well as for the feature of place-of-articulation, but acquired a right ED, i.e., a REA, for the feature of voicing. In terms of the physical characteristics underlying these phonetic features, these subjects remained left-ear dominant for dichotic speech sound pairs differing *only in their spectral composition*, whereas they became right-ear dominant for the sound pair between which the principal difference was *temporal* (VOT). Subject PD's performance closely resembles that of the previous three, with the exception that he became right-ear dominant (in addition to the feature of voicing) also for the vowel sound pairs which differed exclusively or predominantly in their low-frequency formants. However, since this subject did retain his left ED for those vowel sounds which differed only in F2 (Column 6), his results constitute a hint to the effect that low-frequency formants (i.e., the feature [high]) may, in some cases, yield REA, too. To verify this hypothesis, the same subject was tested for four additional vowel pairs: /u/-/U/ (low F1 and low F2), /a/-/ʌ/ (high F1 and low-to-medium F2), /ʌ/ with a regular and with a high F2 (+210 Hz, the F2 corresponding to that of of /a/), and, finally, /a/ with a regular and with a high F1 (+90 Hz, the F1 corresponding to that of /ʌ/).

Results of this experiment are shown in Columns 4-7 of Table 2. For the purpose of comparison, Columns 1-3 of Table 2 repeat subject PD's data on the high front vowels recorded in Columns 4-6 of Table 1. The trend of ear dominance for all vowel pairs indicates that (i) the feature [+high] elicits a switch to REA, whereas the feature [-high] (/a/-/ʌ/) does not, (ii) vowels differing only in F2 (i.e., the acoustic feature corresponding to the front-back distinction) does not make subject PD change his left ED, and (iii) vowels differing only in F1 (i.e., the acoustic feature corresponding to the high-low distinction) always result in a switch to right ED. The most interesting aspect of these results is the dichotomy between [+high]-REA and [-high]-no REA. From the phonetic point of view, this dichotomy suggests that, in some subjects at least, the more "consonantal" high vowels could display

TABLE 1

Ear dominance scores (percentage of responses following stimulus in left ear) of six subjects for dichotic tone pairs (Column 2), vowel- and vowel-like sound pairs (Columns 3-6) and CV pairs (Columns 7-8). Scores larger than 50 % signify left-ear dominance and smaller than 50 % right-ear dominance.

Subject			Stimulus Pair				
	1650 Hz-1750 Hz sine waves	1650 Hz-1750 Hz one-formant vowels	/I/-/ae/ vowels	/I/ with F1 changing	/I/ with F2 changing	/ga/-/ka/	/ba/-/ga/
CB	18	20	18	23	12	20	30
PM	86	90	65	85	74	78	87
AG	100	75	57	55	55	41	66
SP	81	61	54	54	52	32	77
JW	93	95	65	59	62	45	55
PD	100	100	27	16	88	37	89

TABLE 2

Ear dominance scores (see Table 1) for various vowel sound pairs.
One subject (PD) -- strongly left-ear dominant for tones.

Stimulus Pair						
/I/-/ae/	/I/ with F1 (I)-(e) (0)-(+140Hz)	/I/ with F2 (I)-(ɛ) (0)-(-400Hz)	/u/-/U/	/a/-/ʌ/	/ʌ/ with F2 (a)-(ʌ) (0)-(+210Hz)	/a/ with F1 (ʌ)-(a) (0)-(+90Hz)
27	16	88	40	92	98	39

a REA -- just as vowels in a CVC environment have been observed to do (Weiss and House, 1973). From the acoustic standpoint, the dichotomy may be explained by the relative intensity of F2 which, in /a/ and /ʌ/, but not in /I/, /i/, /u/ or /U/, is almost as large as that of F1. Thus, in the [-high] vowels, the prominence of F1 is all but overridden by F2. In sum, the rule for this subject seems to be that, whenever the difference between the F1's of the two dichotic vowels is perceptually more salient than that between the two F2's, he acquires a REA, whereas whenever it is the difference between the F2's which is the more likely cue for distinguishing the two vowels, he retains his natural left ear dominance. But the frequency of first-formant peaks is generally equal to or lower than 500 Hz. Since the temporal structure of the waveform (i.e., periodicity) plays a far greater role in the encoding of low frequencies than does the spatial structure (i.e., spectrum, see Moore, 1973), it is quite possible that Subject PD's right-ear dominance for low-formant (i.e., high tongue-position) vowels may also reflect a REA for temporal stimulus attributes.

The conclusion of these results is twofold: (i) Right-ear advantage for speech sounds is, indeed, contaminated by the subject's ear dominance for spectral information which, quite probably, reflects no hemispheric dominance whatsoever. (ii) Subjects who are left-ear dominant for spectral information will remain left-ear dominant for the processing of those phonetic features which are predominantly spectral, whereas they become right-ear dominant for those features which are predominantly temporal. In other words, results of this study suggest that right-ear advantage for speech consists exclusively in an ear superiority for the processing of temporal information. It just happens that speech represents the temporally-complex acoustic stimulus to which man is most exposed and for which a right-ear advantage is the most easily demonstrated in the laboratory. A corollary to this conclusion is that the functional role of the left posterior temporal lobe (the "speech hemisphere") may not be anything else than keeping track of the temporal organization of (spectrally) distinct acoustic events. However, processing of spectral information in auditory stimuli, including that of spectrally-bound phonetic features of speech sounds, has to be completed prior to the processing of their temporal organization. Because the ear advantage for such phonetic features appears to follow a peripherally-anchored ear superiority for spectral information processing, phonetic analysis in the spectral domain must be accomplished at some definitely subcortical level.

In all fairness, the proposition that man may not use his cortex for phonetic analysis *per se* to the extent which he has been widely believed to do, may sound shocking to some. However, one should keep in mind that, if the role of the cortex were indeed less important for phonetic analysis than it has seemed to be, the brain would become more free to handle all sorts of other, higher level activities -- for example, language processing. Or, as a matter of fact, thinking.

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