FUNCTIONAL ASYMMETRY OF THE BRAIN IN DICHOTIC LISTENING[1]

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Most of the studies I will be describing have been done with normal subjects, but I want first to review briefly some clinical studies which provide a background for the normal data. This work originated at the Montreal Neurological Institute while I was doing research, with Dr. Brenda Milner, on the functional differentiation of the right and left temporal lobes. One of the tests employed in investigating deficits associated with temporal-lobe lesions was the Broadbent (1954) technique. Two different digits are presented simultaneously to the two ears through earphones, one digit to the left ear, the other to the right ear. Usually, three such pairs are presented in rapid succession, and at the end of the six digits, the subject is asked to report all the numbers he heard, in any order he likes. The term "dichotic" has come into use to describe the simultaneous presentation of different stimuli to the two ears.

Background Studies

Damage to the left temporal lobe impaired overall performance on the dichotic digits task (Kimura, 1961a), i.e., the total number of digits correctly reported was smaller for the group of patients with lesions of the left temporal lobe than for the group with lesions of the right temporal lobe (Table I). The difference between groups was present before operation and it was accentuated after operation.

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TABLE I

Digits Test: Mean Total Score

Group	N	Pre	Post	P
Left Temporal	29	161.2 (84%)	153.6 (80%)	< .01
Right Temporal	32	173.8 (91%)	171.9 (89%)	NS

This finding was consistent with other reports that lesions of the left temporal lobe impaired the ability to assimilate verbal auditory material (Meyer and Yates, 1955; Milner, 1958), i.e., that the left temporal lobe had some critical functional role in the perception of spoken material, which the right temporal lobe did not share.

Another more novel finding emerged from the use of the dichotic digits test. Before operation, regardless of the site or side of the lesion, more digits were accurately reported from the right ear than from the left ear, by all patient groups. The same effect was found in normal subjects as well (Kimura, 1961b). The score was higher for the ear opposite the dominant hemisphere than for the ear ipsilateral to it.

Electrophysiological evidence from animal studies suggests that the crossed auditory pathways are stronger than the uncrossed (Rosenzweig, 1951; Tunturi, 1946), and our data on patients with temporal-lobe lesions confirm suggestions by Bocca, Calearo, Cassinari and Migliavacca (1955), and by Sinha (1959), that the same holds true for man. Thus each ear has connections with the auditory receiving area in each hemisphere, but the pathways connecting the ears to their opposite hemispheres are apparently more effective than the ipsilateral pathways.

The explanation for the right-ear superiority on the digits test, then, was that the right ear had better connections with the left hemisphere than did the left ear, and since the left hemisphere was the one in which speech sounds were presumably analyzed, the right-ear sounds had the advantage of having better access to these speech centres.

In the case where speech is represented in the right hemisphere, however, the opposite pattern of ear-superiority should occur, since here it is the left ear which has the favoured connections. A small group of patients with speech represented in the right hemisphere, as determined by the sodium amytal technique (Wada and Rasmussen, 1960), had been tested in the course of the study. Table II compares

TABLE II

Digits Test: Hemisphere Dominance and Preoperative Scores for Right and Left Ears

Locus of Speech	N	Left Ear	Right Ear	P
Left Hemisphere	107	76.6 (80%)	83.0 (86%)	< .001
Right Hemisphere	13	85.0 (89%)	74.9 (78%)	< .01

the relative ear superiority of the two groups, one with speech in the left hemisphere, the other with speech in the right hemisphere. As predicted, the left ear is superior in the right-dominant group. It is the ear opposite the dominant hemisphere which has the higher score in each case (Kimura, 1961b).

It might be objected that the right-dominant group has a higher proportion of patients with severe left-hemisphere damage, and that such damage might depress performance on the contralateral (right) ear, resulting in a spurious superiority of the left ear. Two of the 13 right-dominant patients did in fact have a right-sided hemiparesis, indicating severe damage to the left hemisphere. The ear-accuracy scores for the remaining 11 patients are shown in Table III. Of

TABLE III

Digits Test: Groups Compared for Site and Extent of Damage

Locus of Speech	N	Left Ear	Right Ear	Proportion of Effect
Right Hemisphere (Widespread damage left)	7	79.3 (83%)	72.6 (76%)	6/7
Right Hemisphere (Primary damage right)	4	90.0 (94%)	82.2 (86%)	4/4
Left Hemisphere (Widespread damage left)	8	73.4 (76%)	81.5 (85%)	6/8*

* One patient shows no difference between ears, and one has a higher score for the left ear.

these 11 patients, only 7 have significant damage to the left hemisphere. In the remaining four patients, 3 have only right-hemisphere damage, and one has bilateral damage, predominantly right. All of the latter group have higher scores for the left ear, making it clear that the left-ear superiority is not related to the site of the damage in the right-dominant group.

As a further control for the effects of left-hemisphere damage, cases were sought in whom, despite widespread damage to the left hemisphere, speech functions were nevertheless still vested in that hemisphere. The number of such cases (eight) is understandably small, but they show the right-ear superiority (Table III) typical of other patients with speech represented on the left and this pattern is opposite that of the right-dominant group.

I do not mean to suggest that severe damage to a hemisphere can never reverse the effects of speech dominance on the relative ear score, but merely to make the point that the left-ear superiority in our right-dominant cases cannot be accounted for in terms of site or severity of brain damage.

Neither is the ear pattern directly related to handedness. Table IV compares two groups of patients, both of whom are left-handed, but

TABLE IV

Digits Test: Ear Comparison in Left-Handed Groups

Locus of Speech	N	Left Ear	Right Ear	P
Left Hemisphere	13	73.4 (76%)	80.8 (84%)	$< .01$
Right Hemisphere (All patients)	9	82.9 (86%)	71.6 (75%)	$< .01$
Right Hemisphere (No right hemiparesis)	7	82.1 (85%)	72.4 (75%)	$< .01$

have speech represented in opposite hemispheres. Again, the relative ear superiority takes opposite directions, depending on which hemisphere is dominant for speech.

It should be emphasized that the independence of ear asymmetry from handedness can only be demonstrated *when the speech representation pattern is known.* Where speech representation is not known, as is invariably the case in normal subjects, one would expect the ear pattern to be related to handedness only insofar as cerebral dominance for speech is related to handedness. From their work with the amytal technique on a clinical population, Branch, Milner and Rasmussen (1964) estimate that 90% of normal right-handers and over 60% of normal left-handers have speech functions represented in the left hemisphere. The difference in ear-asymmetry patterns between normal right- and left-handers has been found to correspond roughly to this estimate (Bryden, 1965; Satz, Achenbach, Pattishall and Fennell, 1965).

The evidence is thus overwhelming that the asymmetrical functioning of the two halves of the brain for speech is reflected in unequal perception of words presented dichotically to left and right ears. In an unselected group of normal subjects, speech functions will be represented predominantly in the left hemisphere, and the left cerebral dominance will be reflected in a right-ear superiority on the dichotic digits test.

The Development of Cerebral Dominance

Auditory asymmetry for the perception of dichotically-presented speech sounds provides us with a new technique for the study of cerebral dominance, and one of the most promising areas of research opened up by this technique has to do with the development of brain asymmetry. The age at which the left hemisphere becomes specialized for speech functions has been a focus of concern for some time. It seemed obvious that one should be able to use the presence of a right-ear superiority for spoken digits, as an index of the age at which the left hemisphere takes over speech functions.

The first such developmental study was done in a well-to-do residential area in Montreal. Many of the parents were professionals and the children had above-average IQ's. The children there were tested from age five upwards, and it was found that both boys and girls showed a right-ear effect as early as age five. I subsequently tested some four-year-old children in a nursery school in a comparable area, and here also both boys and girls showed a significant right-ear superiority (Kimura, 1963).

These findings suggested that speech functions were already predominantly represented in the left hemisphere as early as age four. At first glance, this seems at variance with neurological studies on the recovery of language function after injury to the speech areas in the left hemisphere. Such studies generally indicate that apparently complete recovery can occur at a much later age than four or five, and it was concluded from this that speech functions did not become fixed in the left hemisphere until later (See Zangwill, 1960). The data from the dichotic listening study on children, however, suggests that the left hemisphere is prepotent for speech at a very early age. A left-hemisphere predominance for speech functions at an early age does not rule out greater flexibility of organization in the young child, nor does it rule out the potential or actual participation of the other hemisphere in these same functions. Other areas of the brain may be better able to substitute for the speech areas when injury occurs at age five than when it occurs at age fifteen.

This first developmental study was carried out on children of a high socio-economic background. The findings were later replicated in California, with children of a similar background. I subsequently had occasion to repeat the study in Hamilton, in a school which was in a low-to-middle-class socio-economic area. Here I found that, although the five-year-old girls showed a significant right-ear effect, the five-year-old boys did not. They showed a trend for the right ear to be superior, but it was not statistically significant. Next year, a research assistant repeated the study in a comparable school, and found the same thing, that is, the girls showed a right-ear superiority but the effect for the boys fell short of significance. The data from the two schools were so very comparable that they were combined, and the results are shown in Table V. All age-sex groups show a

TABLE V

Mean Number of Digits Correctly Reported for Each Ear

Girls

Age	N	Left Ear	Right Ear	*t* ratio
5	18	11.6	21.8	3.29**
6	16	13.1	22.2	2.92*
7	18	15.3	26.8	3.18**
8	18	19.0	28.3	2.99**

Boys

Age	N	Left Ear	Right Ear	*t* ratio
5	20	15.2	18.9	1.32 NS
6	18	13.6	23.6	3.69**
7	15	12.1	25.0	4.00**
8	17	18.4	26.6	3.11**

* $P < .02$, ** $P < .01$

significant right-ear superiority except the five-year-old boys. Of the 20 boys in this group, 11 have higher scores for the right ear, 8 have higher scores for the left ear, and 1 shows no difference between ears.

It thus appears that if one tests children at an early enough stage of development, a sex difference in the development of cerebral dominance may be detected. The subjects of the latter study, though normal children, were presumably at a somewhat earlier stage in the development of cognitive functions than were the children of the original study (Kimura, 1963). It must be emphasized that we have no information to indicate which of the many factors differentiating the two samples, e.g., intelligence level, home background, verbal ability, are critical.

The data do suggest that boys may lag behind girls in the development of left-hemisphere dominance for speech. This finding has a parallel in Ghent's (1961) demonstration of a lag in the development of somesthetic asymmetry in boys. Ghent has pointed out that a slower development of functional asymmetry of the two hemispheres in boys would be in accord with their slower development of speech (see Terman and Tyler, 1954). Further indirect support for a sex difference in the development of left-hemisphere dominance comes from a study by Taylor (1962) on children with reading disability. The boys of his sample, but not the girls, failed to show a right-ear effect, though they were of an age (7 to 11) when it is present in normal children. Both Taylor (personal communication) and I have found a right-ear effect in older boys with reading difficulties. Apparently, the normal developmental lag is simply accentuated in boys with reading problems.

Mechanisms in Dichotic Listening

To return to the adult studies, it fairly early became clear that the normal auditory asymmetries could be demonstrated only with dichotic presentation, that is, with different stimuli presented to the two ears simultaneously. When digits are alternated rapidly between ears, but do not actually overlap, there is only a non-significant trend for the right ear to be better (Table VI). When stimuli are presented strictly to one ear, as in the monaural presentation of filtered speech (Calearo and Antonelli, 1963), there is no difference whatever between ears. The slight trend for the right ear to be better under our alternating condition is probably due to the fact that it permits some competition between ears which is not present under a straightforward monaural presentation.

TABLE VI

Digits Test: Two Presentation Conditions (N = 35 Normal Subjects)

	Right-Left	t ratio
Dichotic	4.0	4.34*
Successive	.4	1.56 NS

* $P < .01$

Why competition between ears should be necessary for an asymmetry to be demonstrated is of course an interesting question. Part of the answer probably lies in the way in which the auditory pathways are arranged. This arrangement is shown schematically in Figure 1. It suggests that the auditory receiving area receives only

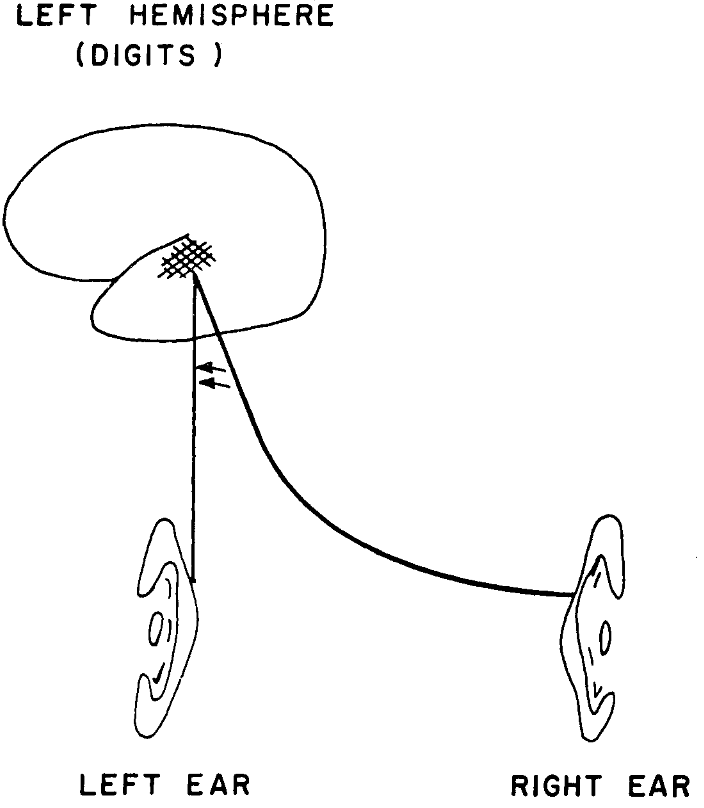

Fig. 1 — *Schematic representation of the auditory pathways to the left hemisphere.*

a slightly greater number of fibres from the contralateral than from the ipsilateral ear. Rosenzweig (1951), however, has proposed that there is in addition a point of overlap between the two pathways, and that at this point of overlap the contralateral pathways are capable of occluding impulses arriving along the ipsilateral pathways. The occlusion mechanism is represented in Figure 1 by arrows. When different stimuli are presented to the two ears, as is the case in the dichotic condition, the impulses arriving along the ipsilateral pathway would be partially occluded, and thus the advantage of the contralateral over the ipsilateral pathway would be enhanced.

Afferent overlap of this type may not be the total explanation for the sensitivity of dichotic presentation to asymmetry. Presumably there is the factor of central occlusion as well, i.e., when two different speech sounds must compete for overlapping pathways in the dominant hemisphere, the slight advantage of the contralateral input over the ipsilateral may be further enhanced by central competition.

Although *hearing* different stimuli at the two ears appears to be a necessary condition for obtaining the perceptual asymmetry, *reporting* the stimuli from both ears is not. This was demonstrated simply by presenting stimuli dichotically, but having the subject report only one ear. A series of four unisyllabic words was presented to the left ear at the same time that four other words were presented to the right ear. The dichotic pairs had the same middle vowel sound, but different consonant sounds at the beginning and end. The subject was asked either to report the left ear only, or he was asked to report the right ear only, different subjects reporting left and right ears. The same list of words as had been presented to the reported ear was shortly afterwards presented monaurally, with no competing sounds in the other ear, and the subject again reported all the words he could. Table VII shows that subjects who reported the right ear had much higher scores than those who reported the left ear, under the dichotic condition. The right-ear superiority does not

TABLE VII

Report of Words from One Ear Only

	N	Dichotic		Monaural
Left Ear Score	13	15.3 (38%)	$P < .001$	34.6 (86%)
Right Ear Score	13	23.5 (59%)		32.3 (81%)

of course appear under the monaural condition. Keep in mind that both conditions require only monaural report. The difference between them is that under the dichotic condition irrelevant words are arriving at the other ear.

The right-ear superiority demonstrated in this study with monaural report must reflect a competition between stimulus inputs to the two ears, that is, a perceptual rivalry rather than a response rivalry. It provides a clear refutation of the position (Inglis, 1965) that the right-ear superiority is in some way dependent on the order in which stimuli are reported from the two ears, since in the present study, only one ear must be reported. Moreover, the number of "words" reported under the dichotic condition from the two ears does not differ significantly (35.8 for the left, 37.9 for the right). What does differentiate the scores for the left and right ears is the number of errors made. Deliberate manipulations of the report order between ears, with both ears reported, does of course affect the accuracy scores, but even so, a right-ear superiority remains (Bryden, 1963; Satz, Achenbach, Pattishall and Fennell, 1965). It also appears under a multiple-choice recognition condition, where there is no report of the stimuli *per se* (Broadbent and Gregory, 1964).

Functional Differentiation Between Hemispheres

Finally, I would like to talk about another line of research to which the dichotic technique may be applied. This has to do with the further delineation of function between the left and right hemispheres. So far, we have been concerned only with spoken digits and words, verbal stimuli dependent on the left hemisphere for accurate recognition. Certain nonverbal auditory stimuli, however, are processed primarily by the right hemisphere. Milner (1962) has shown that performance on some subtests of the Seashore Measures of Musical Talents is affected by right temporal lobectomy, but not by left temporal lobectomy. The findings indicate that tonal pattern perception, for example, depends more on right temporal activity than on left temporal activity.

It should follow, then, that a relative ear superiority for melodic patterns could also be elicited, and that it would be in a direction opposite to that for spoken digits. To test this, a melodies task was devised which employed a multiple-choice recognition technique. Two different melodies were presented dichotically, and they subsequently had to be picked out from a group of four melodies, two of which had not been presented. Details of the procedure are given in the original report (Kimura, 1964). The multiple-choice method was chosen because the melodies were not familiar to most of the subjects, and it was not feasible to have the subjects reproduce them.

The melodies test was presented to a group of normal subjects. A significantly greater number of accurate identifications was made for the left ear than for the right ear (Table VIII). On the digits

TABLE VIII

Ear Comparison on Two Auditory Tasks (N = 20 Normal Subjects)

	Left Ear	Right Ear	P
Melodies	13.6 (75%)	11.3 (63%)	$< .01$
Digitis	86.6 (90%)	90.3 (94%)	$< .02$

test, the same subjects had a higher score for the right ear. Although the melodies test was devised for normal subjects, it was expected from Milner's (1962) findings that right temporal lobectomy would impair performance on it as a whole, and this prediction was also borne out (Shankweiler, 1966).

We have, then, a clear dissociation of auditory asymmetries, depending on the type of stimulus presented, and these asymmetries in turn reflect differences in function between left and right hemispheres. The proposed neuroanatomical basis for the dual auditory asymmetry is summarized in Figure 2. It is similar to Figure 1, but with the addition of pathways to the right hemisphere. It shows schematically both the connections between each ear and each auditory cortex, and the functional differentiation between left and right hemispheres. The predominance of the right temporal lobe in the assimilation of melodic patterns is reflected in a left-ear superiority, and the predominance of the left temporal lobe in the perception of words is reflected in a right-ear superiority.

We thus have a means, within the limitations of the dichotic technique, for studying further the division of labour between the left and right hemispheres of the brain. By varying the stimulus dimensions, we may be able to define more explicitly just what characteristics differentiate stimuli depending more for their perception on the left hemisphere, from those depending more on the right hemisphere. That is, we can ask which stimulus characteristics are associated with a right- or a left-ear superiority.

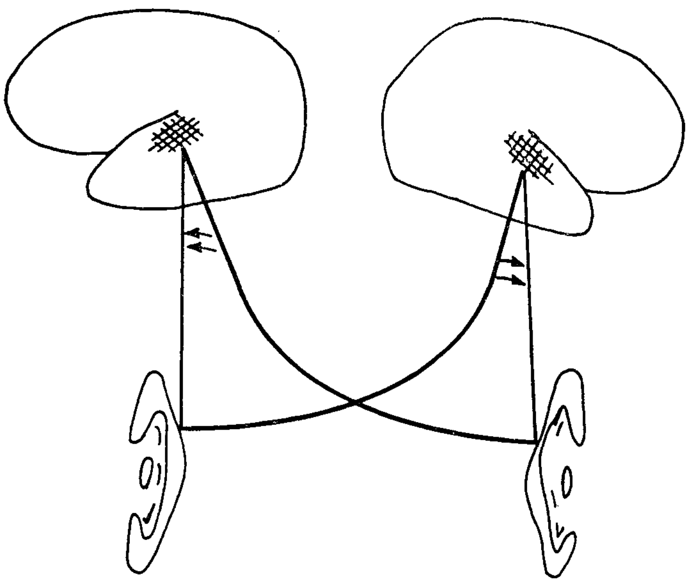

Fig. 2 — *Neuroanatomical schema for the auditory asymmetries.*

One characteristic which seems to characterize left-hemisphere-dependent stimuli is a high degree of familiarity. Digits and words are familiar stimuli and show a right-ear superiority. The melodies, which were woodwind passages unfamiliar to the subjects who listened to them, showed a left-ear effect. Analogous asymmetries demonstrated in the visual modality (Kimura, 1966) could also be interpreted as organized along the familiar-unfamiliar dimension. It therefore seemed important to determine whether a right-ear superiority obtained with all familiar stimuli, even those which do not have ready verbal labels.

Perhaps the best example of a stimulus which can be familiar but not easily named is a familiar melodic pattern. It happens that it is difficult to evaluate the effects of a brain lesion in this case. Non-recognition of a supposedly familiar melody in the presence of a brain lesion may not necessarily indicate a *loss* of recognition. It may only indicate that familiarity with the melody was never acquired. In this case, it is especially appropriate to use normal subjects, since one can determine both the degree of familiarity of several melodies, and the ease with which the same melodies arriving at left and right ears are perceived, i.e., one can unambiguously relate hemispheric specialization of function to the dimension of familiarity.

The next study was therefore intended to answer the question whether familiar melodic patterns showed a different hemispheric representation from unfamiliar melodic patterns. A series of very familiar concert melodies was chosen which could not easily be identified by name — passages from symphonies, concertoes, etc. The melodies were played in dichotic pairs to experienced music listeners, and the subject hummed the melodies immediately after he heard them. Usually he managed to hum only one of the melodies. At the end of the test, each melody was played again, singly, and the subject was asked, first, if it was familiar to him, and second, if he could identify it. Approximately 75% of the melodies, on the average, were familiar to the subjects, but very few were identified correctly. This is a phenomenon which will be familiar to most music listeners.

The ear comparisons are shown in Table IX. On the test as a

TABLE IX

Ear Comparison for Familiar Melodies (N = 16)

	Left Ear	Right Ear	P
Humming Melodies	3.3 (37%)	2.1 (23%)	< .05
Humming Melodies (Familiar Pairs Only)	3.0 (33%)	1.6 (18%)	< .01
Repeating Digits	44.0 (81%)	48.3 (89%)	< .05

whole, humming of melodies arriving at the left ear was more frequent than for those arriving at the right ear. (The low overall score was due partly to the difficulty the experimenter had in deciding what was being hummed. Only those melodies for which there was no doubt were scored as correct.) The second comparison is based on only those dichotic pairs in which *both* melodies of the pair were familiar, as indicated by the subject's subsequent evaluation. This is the more critical analysis, since here we have two familiar melodies competing. Again, there is a clear left-ear superiority. On the digits test, there is the typical right-ear superiority. It thus appears that even familiar melodic patterns have their major representation in the right hemisphere. Familiarity, of itself, does not appear to be a critical factor in hemispheric specialization of function.

We must look to some other characteristic of digits and words to account for the right-ear effect. To say that they are verbal stimuli and that verbal processes are vested in the left hemisphere is only an apparent explanation, since it is not at all clear what verbal activity consists in. Indeed, it is the very possibility of indirectly studying the nature of verbal activity which makes the application of these perceptual techniques so promising. A very small beginning in this direction has been made by studying the ear-asymmetry pattern for one kind of non-meaningful sound, the nonsense syllable. The nonsense syllable, although it contains elements used in meaningful speech, should not in itself evoke any degree of conceptualization. Nonsense syllables of low association value were first presented in the same way that words had previously been presented, i.e., dichotic presentation of a series of syllables, with monaural report. The results were very much the same as for words (Table X), the right ear being

TABLE X

Report of Nonsense Syllables from One Ear Only

	N	Dichotic		Monaural
Left Ear Score	13	6.1 (15%)	$P < .02$	17.9 (45%)
Right Ear Score	13	10.4 (26%)		18.5 (46%)

reported much more accurately than the left. It is possible, however, that making the subject *say* the syllables might bias the effect in favour of the right ear. A second study was therefore done, employing the multiple-choice recognition procedure previously used for melodies. Instead of a single nonsense syllable, three syllables were spoken in quick succession, making one long nonsense sound. Two of these complex sounds were presented dichotically, to be picked out from four sounds which followed. More sounds were again correctly identified for the right ear than for the left ear (Table XI) despite the fact that the subject did not have to report any of the sounds.

These data indicate that the processing of spoken nonsense sounds is carried out by the left hemisphere, just as is spoken meaningful material. By implication, the subunits of speech, as well as words, are

TABLE XI

Ear Comparison for Nonsense Speech: Recognition Method (N = 20)

Left Ear	Right Ear	P
5.6 (47%)	8.1 (68%)	< .01

asymmetrically represented. Investigators at Haskins Laboratories (Liberman, Cooper, Harris and MacNeilage, 1962) have suggested that much of speech is perceived by reference to articulation experience. Conceivably, then, the features of speech sounds which distinguish them from non-speech sounds are related to articulability rather than to conceptual content. In this context, it is of interest that vowels show a much weaker right-ear effect than consonant-vowel syllables (Shankweiler and Studdert-Kennedy, 1967).

Summary

This paper reviews the evidence relating lateral asymmetry in auditory perception to the asymmetrical functioning of the two hemispheres of the brain. Because each ear has greater neural representation in the opposite cerebral hemisphere, the predominance of the left hemispere for speech is reflected in superior recognition for words arriving at the right ear, while the predominance of the right hemisphere in melodic-pattern perception is reflected in superior identification of melodies arriving at the left ear. Some applications of the dichotic listening technique to questions concerned with the development of cerebral dominance, and with the further specification of function of the left and right hemispheres, are also described.

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