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Dichotic listening after cerebral hemispherectomy: Methodological and theoretical observations☆

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Abstract

We examined two commonly used dichotic listening tests for measuring the degree of hemispheric specialization for language in individuals who had undergone cerebral hemispherectomy: the consonant–vowel (CV) nonsense syllables and the fused words (FW) tests, using the common laterality indices *f* and λ. Hemispherectomy on either side resulted in a massive contralateral ear advantage, demonstrating nearly complete ipsilateral suppression of the left ear in the right hemispherectomy group but slightly less complete suppression of the right ear in the left hemispherectomy group. The results are consistent with the anatomical model of the ear advantage [Kimura, D. (1961). Most syllables or words are reported for the ear contralateral to the remaining hemisphere, while few or none are reported for the ear ipsilateral to the remaining hemisphere. In the presence of competing inputs to the two ears, the stronger contralateral ear-hemisphere connection dominates/suppresses the weaker ipsilateral ear-hemisphere connection. The λ index was similar in the two tests but the index *f* was higher in the CV than the FW test. Both indices of the CV test were sensitive to side of resection, higher in the right hemispherectomy than in the left hemispherectomy groups.
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Keywords: Dichotic listening; Laterality indices; Hemispherectomy; Ipsilateral suppression

1. Introduction

Dichotic listening (DL) is a non-invasive method for measuring cerebral hemispheric specialization of auditory processing. A general right ear advantage (REA) for verbal material and a left ear advantage (LEA) for non-linguistic stimuli have been demonstrated in healthy individuals (Berlin & McNeil, 1976; Kimura, 1961). The ear advantage is attributed to the dominance of the contralateral cerebral hemisphere for processing the stimuli. Kimura's anatomical model posits that although both ears are represented in both hemispheres, the ipsilateral connections are weaker and suppressed during simultaneous presentations of similar auditory stimuli. As a result, each ear primarily projects to the contralateral cerebral hemisphere, and more accurate responses from one ear are interpreted to reflect the specialization of the contralateral hemisphere for processing the stimuli (Zaidel, 1979a). However, different dichotic listening tests yield different degrees of hemispheric specialization and create different degrees of ipsilateral suppression. Dichotic listening tests are therefore differentially susceptible to attention and memory load. Kinsbourne (1975) proposed an alternative, attentional, model of the ear advantage. In their view, hemispheric specialization is associated with attention shifts to the contralateral half of space. Indeed, attentional focus can modulate incomplete suppression (Zaidel, 1983), and there appear to exist separate auditory channels for attended and unattended information. However, the attentional model was not supported by the only reported case of dichotic listening during forced attention in a patient with left hemispherectomy (Wester,

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Hugdahl, & Asbjornsen, 1991). This study revealed a complete right ear extinction irrespective of attentional instruction.

The dichotic listening technique has been used to explore laterality effects in subjects with agenesis of the corpus callosum, partial and complete commissurotomy (e.g., Zaidel, 1983), congenital hemiplegia (Isaacs, Chrisie, Vargha-Khadem, & Mishkin, 1996; Korkman & von Wendt, 1995), acquired and congenital brain injury (Nass, Sadler, & Sidtis, 1992) and cortical hemispherectomy (Damasio, Lima, & Damasio, 1975; Netley, 1972; Zaidel, 1979b). The results of these studies suggest that the ear advantage in dichotic listening is a valid measure of hemispheric specialization (Zaidel, 1978) and that a reduced overall ear score can indicate abnormal hemispheric specialization. Reversed speech lateralization as measured by a left ear advantage was documented in many of these studies, although care must be taken to distinguish a reduced ear score due to a contralateral lesion effect from a true shift of language dominance. The timing of a lesion and its underlying pathology, as well as presence of seizures, was shown to influence the degree of lateralization as measured by the ear advantage. Congenital lesions seem to reduce the magnitude of abnormal laterality, possibly due to increased cortical reorganization (Fernandes & Smith, 2000; Woods, 1984).

While research of the lesion effects on laterality as studied by the dichotic listening methods clarifies the conditions and limits of cortical plasticity, studies involving post-hemispherectomy individuals may be particularly valuable for elucidating the mechanism of dichotic listening and for validating existing methods. Thus, it can test the assumption of the anatomical model of the right ear advantage in dichotic listening to linguistic stimuli, namely, complete ipsilateral suppression on both sides and exclusive left hemisphere specialization for language. The assumption of exclusive specialization can be best tested in patients with complete cerebral commisurotomy (Zaidel, 1978, 1979a,b, 1983). However, an even better preparation for assessing ipsilateral suppression is provided in cases of right and left hemispherectomy because they exclude possible subcortical interhemispheric communication, which may occur in the split brain.

Cases of hemispherectomy due to early lesions are likely to show language reorganization and may not reflect normal hemispheric competence. Following cerebral hemispherectomy, the ear ipsilateral to the lesion is expected to show complete extinction (Zaidel, 1983). Indeed, this finding was reported in 12 post-hemispherectomy individuals studied by Netley (1972) in a dichotic listening paradigm involving digits (triads). The poorest performance on this task was noted in older hemispherectomy patients. Similar results were reported in two hemispherectomy patients studied by Zaidel (1979b) and one patient studied by Wester et al. (1991) using the dichotic consonant–vowel (CV) nonsense syllable paradigm.

The methodological goal of the present study was to examine the validity of two commonly used dichotic listening tests for language dominance as well as of two commonly used laterality indices in post-hemispherectomy individuals. The theoretical goal of the study was to measure the ear advantage and its relation to language competence, which is quite variable, following left and right cerebral hemispherectomy. We administered two language-based dichotic listening tests, the dichotic nonsense consonant–vowel syllable test and the Dichotic Fused Words, FW, test (Wexler & Halwes, 1985), and we used two laterality indices, f and λ. The CV test measures hemispheric specialization for phonetic perception, whereas the FW test measures also language comprehension. The laterality index of f normalizes the ear difference score by total accuracy and is especially important when the difference in the hemispheric scores correlates with overall performance (Zaidel, 1979a,b). λ shares a similar function of overall ability and provides, in addition, a statistical measure of significance (Bryden & Sprott, 1981). Specifically, we investigated the competence of the isolated left and right cortical hemispheres, the degree of suppression of the ipsilateral connections, as well as validity and reliability of the laterality indices of the two tests.

2. Subjects

Fourteen individuals from UCLA's Pediatric Epilepsy Surgery Program who have undergone cerebral hemispherectomy participated in this study (7 males, 7 females, mean age 12 years and 6 months, age range 10–22 years). All participants had partial or complete surgical removal and complete functional disconnection of one cerebral hemisphere to control catastrophic childhood epilepsy associated with perinatal infarct, Rasmussen encephalitis (RE) or cortical dysplasia (CD), (Jonas et al., 2004). Three patients underwent anatomic, 5 the Rasmussen functional and 6 the UCLA modified hemispherotomy procedures as previously described (Cook et al., 2004). In all procedures the auditory cortex along the superior posterior temporal lobe was removed. Each participant's etiology was based on the medical history, neuropathology report, seizure and antiepileptic drug history, MRI scans, and initial video electroencephalography monitoring. At the time of dichotic listening testing all participants were seizure free (with or without medications), i.e., had no overt seizure activity.

Mental age, MA, was evaluated using Peabody Picture Vocabulary Test (PPVT) language scores that approximate mental ages based on a vocabulary size (Dunn, 1981). Standard hearing tests were administered to every participant. All participants had normal hearing thresholds (20 dB HL or better) at standard octave frequencies from 250 to 8000 Hz in both ears (ANSI, 1996). Clinical variables on each subject are shown in Table 1. The study was approved by the UCLA Institutional Review Board and performed with the written informed consent of both the patients and their legal guardians.

3. Procedures

3.1. Listening tasks

Routine hearing exam was administered to each participant before testing. All listening materials for dichotic tasks were presented using a personal computer (44.1 kHz sampling, 16 bit resolution) and converted to analog form using an Echo Gina24 D/A converter. The signals were delivered at 70 dBA in each

Table 1
Clinical data

Participant/surgery side	Etiology[a]	Age at first seizure (years)	Age at surgery (years)	CA/MA[b] at testing (years)	Examined postoperatively (years)
1/left	RE	4.4	4.6	10.3; 4.5	5.9
2/left	RE	2.3	3.6	11.8; 7.9	8.2
3/left	RE	5.0	10.0	13.9; 9	3.9
4/left	Perinatal infarct	4.0	12.0	11.0	1.0
5/left	Perinatal infarct	5.0	8.4	10.1; 9.4	1.9
6/left	Postnatal infarct	Birth	4.1	22.0; 5.02	17.11
7/left	Perinatal infarct	4.6	10.0	14.4; 8.2	4.4
8/left	CD	5.0	6.9	11; 7.11	4.3
9/left	CD	0.6	1.6	11.6; 9.5	10.0
10/left	CD	Birth	1.11	12.0; 6.7	10.3
11/left	Other	1.6	6.10	21.0; 12.4	14
12/right	RE	2.1	3.5	16.8; 12.8	11.3
13/right	Prenatal infarct	6.0	8.6	12.0; 8.1	3.6
14/right	Postnatal infarct	1.0	8.5	10.2; 8.0	1.9

[a] Rasmussen encephalitis, cortical dysplasia, and infection (other).
[b] CA/MA: chronological/mental age at testing.

ear as measured on a flat plate coupler and Type 1 sound level meter (Larson Davis AE101 and 800B) via Sennheiser HD 250II headphones. Testing took place in a sound-treated booth. Not all participants could read and therefore each individual was instructed to say aloud the syllable or word they heard. An investigator (SdB) remained in the booth and circled the answer on the score sheet.

3.1.1. Consonant–vowel test

Each individual was given the dichotic CV test consisting of the nonsense syllables Ba/Da/Ga/Pa/Ta/Ka. We used the dichotic nonsense syllable (CV) task of the Veteran's Administration-CD Tonal and Speech Materials for Auditory Perception Assessment, Disc 1.0. Thirteen out of fourteen participants were able to complete this task (participant 6 was excluded from analyses of the CV test because she did not pass a practice test). Subjects heard two different syllables in each ear simultaneously. Two runs of 30 stimuli each (total 60 items) were administered. Each possible pair of syllables was presented twice so that both syllables were presented once to the right and left ears during one test run. Participants were generally unaware that two stimuli were presented and were instructed to report aloud the syllable they were most sure of having heard.

3.1.2. Fused Words Test

Each participant was also administered the Dichotic Fused Words test, (Wexler & Halwes, 1983). Stimuli consist of 30 pairs of simultaneously presented rhyming dichotic words which differed on the first consonant only (e.g., beer-pier). The words were temporally aligned and participants were not aware that the stimulus was dichotic. Each individual was asked to repeat aloud the word they heard. Three blocks of 30 stimuli sets were administered (total 90 items). Half of the participants were given this test before the consonant–vowel test.

3.1.3. Binaural condition

The words from the FW test were administered before dichotic presentation binaurally (30 items) to make sure that all subjects were familiar with the words presented.

3.1.4. Monaural condition

The words from the FW test were presented monaurally for a total of 30 stimuli per ear (60 items total).). The monaural presentation always followed the binaural one and preceded the dichotic listening presentation.

3.2. Calculations of laterality indices

Overall accuracy was expressed by the total number of correctly reported words. The results for both dichotic tests were calculated as percentage of correct responses in each ear relative to the total number of items. Ear advantage (EA) was defined as percent difference in accuracy between the two ears. Two additional measures of laterality were calculated for both tests, CV and FW, as follows: $\lambda = \ln(C+1)/(I+1)$ and $f = (\mathrm{C} - I)/(C+I)$ when $(C+I) \leq 100\%$, where C is the proportion of stimuli identified in the ear contralateral to the remaining hemisphere and I is the proportion of stimuli identified in the ear ipsilateral to the remaining hemisphere. Split half reliability test for λ and f for the CV test was calculated between first and second runs, and for the FW test between first and third runs.

4. Results

In our data analysis we divided all participants into those with an isolated right hemisphere (post-left hemispherectomy, LH) and an isolated left hemisphere (post-right hemispherectomy, RH). The right and left hemispherectomy groups did not differ significantly in the following clinical variables: age at seizure

Table 2
Accuracy scores (±S.D.) in monaural, binaural and dichotic listening conditions of the FW test and CV test

	Total score	Contralateral ear	Ipsilateral ear
FW—binaural (30 trials)	0.86 ± 0.12	n/a	n/a
FW—monaural (60 trials)	0.76 ± 0.14	0.78 ± 0.13	0.61 ± 0.16
FW—DL (90 trials)	n/a	0.78 ± 0.1	0.12 ± 0.06
CV—DL (60 trials)	n/a	0.75 ± 0.11	0.06 ± 0.04

onset, age at surgery, age at testing, mental age and time elapsed post-surgery. The laterality measures, λ and *f* were not affected by these clinical variables either. Furthermore, the groups did not differ based on the type of hemispherectomy.

4.1. Accuracy

In the monaural condition of the FW test, accuracy in the ear contralateral to the remaining hemisphere, henceforth "the contralateral ear", (0.78 ± 0.13) was higher than accuracy in the ipsilateral ear (0.64 ± 0.16; p = 0.013, one-tail; Table 2). Accuracy in binaural FW condition (0.86 ± 0.12, P = 0.03) was greater than in the monoraul FW condition (0.76 ± 0.14).

4.2. Dichotic test results

4.2.1. Ear advantage in the CV test

As expected, large ear asymmetries were found in all subjects favoring the ear contralateral to the remaining hemisphere (ear advantage, EA, mean ± S.D.: 0.71 ± 0.14). There was a statistically significant negative correlation between the two ears (r = −0.732, p = 0.009). The individual results are shown in Fig. 1. There was no correlation between the contralateral ear scores and the measure of receptive vocabulary, PPVT.

4.2.2. Ear advantage in the FW test

Ear advantage scores (Fig. 1) demonstrated a strong contralateral ear advantage for the FW test (mean ± S.D. 0.78 ± 0.1). There was a strong negative correlation between the two ears (r = −0.63). Also, the contralateral ear scores correlated with the measure of receptive vocabulary, PPVT (r = 0.587). There were no differences due to side of resection found between the groups of post-hemispherectomy individuals.

4.2.3. The side of the resection and the laterality indices, f and λ

Ear advantage and both λ and *f* were sensitive to the side of the resection and were significantly larger for the RH group but only in the CV test (see Table 3). Right ear scores in the CV test were higher in the RH group (p = 0.002) with left ear sores significantly lower (p = 0.033) than those in the LH group. The RH group's λ index was larger than the LH group (p = 0.0005) as well as *f* (p = 0.002).

Table 3
Means (±S.D.) of stimuli identified by each ear for the CV and FW tests

	Right hemispherectomy		Left hemispherectomy	
	Right ear	Left ear	Left ear	Right ear
CV	0.89 ± 0.06	0.03 ± 0.02	0.74 ± 0.08	0.08 ± 0.03
FW	0.81 ± 0.03	0.10 ± 0.04	0.77 ± 0.1	0.12 ± 0.11

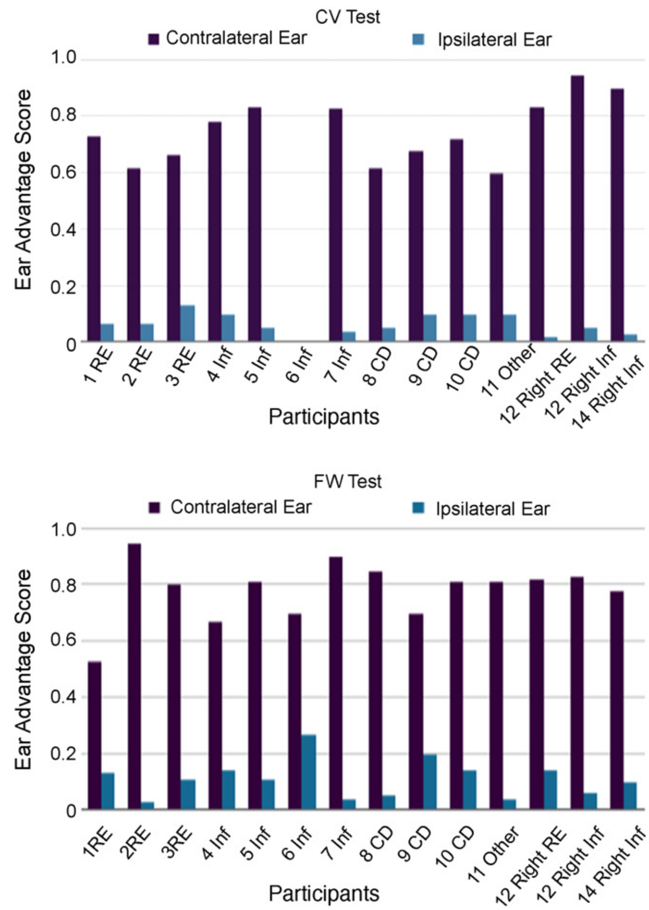

Fig. 1. Dichotic CV and FW tests: individual scores (etiologies listed—RE: Rasmussen encephalitis, Inf: infarct, and CD: cortical dysplasia).

4.3. The laterality indices f and λ

We calculated *f* and λ for the two tests. Mean λ (±S.D.) was similar across the two tests: 2.17 ± 0.69 for the CV test and 1.91 ± 0.62 for the FW test. The mean *f* (±S.D.) was significantly higher in the CV test, 0.84 ± 0.09 than in the FW test, 0.76 ± 0.12 (p = 0.022, t = 2.677).

4.3.1. Split half reliability

Split half reliabilities of the CV test were as follows: λ = 0.95, *f* = 0.44. For the FW test, λ = 0.67, and *f* = 0.77. λ and *f* correlated strongly with each other (Pearson Product) in each test, CV = 0.986 and FW = 0.923.

5. Discussion

We evaluated two commonly used dichotic listening tests, the CV test and the Fused Words Test. We also evaluated two indices of laterality, *f* and λ, in order to determine which are the most reliable measures of functional asymmetry. The laterality index *f* corrects for overall performance level (Zaidel, 1979b). The index λ (Bryden & Sprott, 1981) also corrects for overall performance level and provides a direct measure of the statistical significance of the perceptual asymmetry.

5.1. The anatomical model

The ear asymmetry revealed by the dichotic tests can be explained by the structural/anatomical model where the crossed, contralateral projections are functionally stronger than uncrossed, ipsilateral auditory pathways (Kimura, 1961, 1963). In this model, the stimulus-dominant ear is determined by the specialization of the contralateral hemisphere for processing the stimuli. Following cerebral hemispherectomy, due to the lack of competition between the two hemispheres, it is possible to investigate the underlying assumption of ipsilateral suppression. Berlin and McNeil (1976) argued that ipsilateral suppression occurs at a subcortical level, in the medial geniculate bodies. However, there is evidence that ipsilateral suppression is sensitive to hemispheric specialization, showing a top-down effect (Zaidel, 1978). Further, the comparison between the LH and the RH groups evaluated the relative specialization of the two hemispheres for the linguistic material under conditions favoring plasticity and reorganization. Thus, ipsilateral suppression was measured by the score of the ipsilateral ear, whereas the degree of hemispheric competence was measured by the score of the contralateral ear. Unlike the aphasic brain, neither ear reflects a lesion effect, thus avoiding the ambiguity inherent in interpreting the ear advantage following circumscribed hemispheric lesions.

5.2. Competence

Overall accuracy in individuals post-hemispherectomy, 76% and 86% for monoraul and binaural conditions, respectively, was lower than 90% accuracy reported for children with both brain damage and agenesis of corpus callosum (Di Stefano, Salvadori, Fiaschi, & Viti, 1998). It was also lower than scores we obtained in a routine hearing screening administered to each participant in our cohort at the beginning of the testing.

5.3. Ipsilateral suppression

As expected, both tests exhibited near complete extinction of the ipsilateral pathways and consequently a massive advantage of the ear contralateral to the remaining hemisphere. A significant negative correlation between the two ear scores was found, suggesting that the two ears are in competition for processing resources. This, in turn, suggests that the degree of ipsilateral suppression is directly correlated with hemispheric competence as expressed in the strength of a contralateral connection. Indeed, the ipsilateral ear scores were lower in the RH group than the LH group in both tests, consistent with left hemisphere specialization for language. Similarly, in the RH group, the contralateral ear scores were higher and the ipsilateral ear scores were lower in the CV test than in the FW test.

The magnitude of functional asymmetry for the entire group measured by λ was similar for both tests. The magnitude of functional asymmetry measured by *f* was significantly larger for the CV test than for the FW test ($p = 0.022$). This is in agreement with Bryden and Sprott's (1981) argument that more difficult tests result in larger ear differences as well as larger *f* values and that this happens to younger children who make many errors in the dichotic listening tests. In our study, low mental ages in some participants may result in a performance similar to that in young children since three participants with the lowest CV accuracy scores also had the lowest mental ages.

Comparing the two tests, the CV test proved to be more sensitive to the side of resection than the FW test. The degree of laterality as measured by the λ and *f* indices were significantly higher in the RH group than in the LH group ($p = 0.0005$). This is not surprising given the specialized nature of the stimuli in this test. The isolated left hemisphere (RH group) outperformed the isolated right hemisphere (LH group) in processing nonsense syllables since the left hemisphere is said to be specialized for phonetic analysis. Language reorganization in all participants notwithstanding, the footprints of innate hemispheric competence seem to be present in the RH group, thus increasing the scores in the contralateral ear and suppressing the scores in the ipsilateral ear at the same time relative to the LH group. This finding of more efficient performance in the isolated left than the right hemisphere confirms the results of an event-related study in children after cerebral hemispherectomy (Liasis, Boyd, Rivera-Gaxiola, & Towell, 2003). These authors recorded auditory event-related potential from 17 participants who had undergone hemispherectomy and 10 controls. They reported increased syllable latencies of the ERP components associated with syllables in the group with the isolated right hemisphere.

In contrast to the tests involving syllables, both hemispheres performed similarly when processing words in the FW test. This is expected given that both cerebral hemispheres have semantic competence and auditory language comprehension. Furthermore, our finding that the contralateral ear scores correlated with the measure of receptive vocabulary (PPVT) only in the FW suggests that the FW test may be appropriate when testing for hemispheric specialization for auditory word comprehension is tested.

The fact that there was a larger ipsilateral suppression and a larger *f* for CVs in the LH than in the RH, but equal suppression and laterality indices in both groups on the FW test shows that ipsilateral suppression can be modulated, however subtly, by hemispheric competence. This suggests that ipsilateral suppression is subject to cortical effects (Geffen, 1980) and not entirely subcortical as originally claimed (Berlin & McNeil, 1976). The cortical region and information processing stage at which ipsilateral suppression occurs remain to be determined.

6. Conclusion

Both dichotic tests are good measures of LH specialization for language. Both show massive suppression of the ear ipsilateral to the processing hemisphere and extremely high contralateral ear advantage. Our data show overwhelming capacity for reorganization of language competence in the remaining hemisphere. Nonetheless, there are signs of stable and reliable innate prerequisites for better phonetic analyses in the LH, whereas both hemispheres are equally likely to be involved in auditory language comprehension.

It can be expected that in all modalities stimuli which are contralateral to the lesion will be suppressed to a smaller or greater extent. In the case of auditory linguistic information with good acoustic and temporal overlap between the two ears, the suppression is large. Nonetheless, the degree of hemispheric specialization for the stimuli can modulate the precise degree of suppression. This suggests that suppression is at least partly a top-down cortically controlled process (cf. Geffen, 1980)

The two indices f and λ correlated highly with each other across tests. Split half reliability across tests was higher for the λ index than for the f index. We conclude that the preferred method for measuring hemispheric specialization for phonetic discrimination is the CV test using the λ index. However, the FW test is still a reliable measure when auditory comprehension is tested and was easier to administer when participants had lower mental ages. Given the massive suppression of the ipsilateral ear following cortical hemispherectomy, these patients may neglect conversational partners of the side of the missing hemisphere when experiencing different types of speech inputs to both sides simultaneously.

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