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Controlling for Stimulus Dominance in Dichotic Listening Tests: A Modification of λ

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Dichotic listening procedures have been used to assess cerebral lateralization in normal subjects. One particularly useful technique is the use of stimuli that fuse into a single percept. Although this procedure has many advantages over other dichotic listening methods, it is particularly susceptible to stimulus dominance, which acts as noise in a subject's response data, thus reducing the power of any statistical test of the ear advantage. It is proposed that the solution to this problem is a log-linear analysis of the response data to yield a λ-type index (λ*) that is a measure of ear dominance independent of stimulus dominance. Details of the analysis are provided, as well as a sample analysis of data collected from 104 right-handed and 30 left-handed subjects. Comparisons are drawn between the log-linear analysis and other methods that have been proposed to control for stimulus dominance in this single-response dichotic fusion procedure.

It has been over 30 years since Kimura (1961b) first reported a right-ear advantage (REA) for dichotically presented speech and demonstrated its relation to left-hemisphere speech representation (Kimura, 1961a). Early versions of the task involved dichotic presentation of lists of digits or words, typically between two and four to each ear. There were, however, several problems with this procedure. Subjects normally reported the words from the right ear followed by the words from the left ear, and so the ear advantage was confounded by a short-term memory effect and by the order in which the items were reported. Tasks were developed in which subjects listened to only a pair of words or syllables, reducing the memory load, but the results of these tests were still influenced by the individual's strategies and attentional biases (Bryden, 1978). Several procedures, including directed attention (Bryden, Munhall, & Allard, 1983; Hugdahl & Andersson, 1986) and dichotic cueing (Mondor & Bryden, 1991), indicated that the dichotic ear advantage could be altered by attentional manipulations. The procedure also had only moderate validity in the prediction of side-of-speech representation: Clinical studies suggest that 95% to 99% of right-handers have left-hemisphere speech (Segalowitz & Bryden, 1983) but that only about 80% of subjects have a right-ear advantage (Bryden, 1988). The dichotic monitoring technique (Geffen, Traub, & Stierman, 1978), in which subjects listen for a target in a dichotic stream of speech, has been reported to have better validity, yet Geffen and Caudrey (1981) could correctly classify only 31 of 37 subjects of known speech lateralization on the basis of the direction of ear advantage.[1]

While changes were being made to the dichotic listening procedure, advances in audio technology allowed for great improvements in the quality of stimuli. Studdert-Kennedy and Shankweiler (1970) were able to produce high-quality stimuli with excellent temporal resolution. They presented pairs of consonant–vowel (CV) syllables, using the six stop consonants (i.e., /ba/da/ga/ka/pa/ta/). The dichotic syllables were so precisely aligned that subjects often perceived only one–a phenomenon known as *dichotic fusion* (Halwes, 1970; Repp, 1977). Wexler and Halwes (1983) took advantage of this dichotic fusion in their preparation of the Fused Dichotic Words Test. Pairs of rhyming words were temporally aligned so as to fuse into a single percept. Subjects were not even informed that words were presented dichotically and were asked only to report the single word they had heard. This procedure is free of most of the methodological flaws inherent in other methods. Only one response is given on each trial, eliminating the order-of-report problem, and the results are not influenced by at-tentional manipulations (Asbjornsen, Hugdahl, & Bryden, 1993; Halwes, 1970; Whitaker, 1983). The procedure also has better validity than other dichotic methods. Zatorre (1989) found that of 35 subjects known to have left-hemisphere speech (as determined by the sodium amytal procedure), 33 had an REA on the fused words test. Four of 4 subjects with right-hemisphere speech exhibited a left-ear advantage (LEA). The difficulty with the procedure was that subjects with

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[1] By combining handedness information with dichotic monitoring information, Geffen and Caudrey (1981) were able to correctly classify 35 of 37 subjects.

bilateral speech representation produced both REAs and LEAs, and no adequate cutoff point could be defined that classified subjects into left, right, and bilateral groups.

The presence of three language groups means that the simple REA/LEA distinction is inadequate. What is needed is an index of degree of lateralization. One would presume that subjects with left- and right-hemisphere speech would have large REAs and LEAs, respectively, and that those with bilateral speech would exhibit small ear advantages (either REAs or LEAs). Various laterality indices have been proposed, based on the relative proportions of right- and left-ear scores (Harshman & Krashen, 1972; Marshall, Caplan, & Holmes, 1975). One of the most commonly used laterality indices is λ (Bryden & Sprott, 1981), which in the case of this single-response procedure is the natural log-odds ratio of right-ear responses to left-ear responses. Lambda is statistically very useful, as it is unbounded, is approximately normally distributed, and is unconstrained by accuracy. Most important, it has a standard error associated with it, so that the significance of an individual ear advantage can be assessed. Wexler, Halwes, and Heninger (1981) suggested that the use of an appropriate significance criterion when examining dichotic data yields proportions of REAs and LEAs that parallel those found in clinical populations. Although only 80% of right-handed subjects may have an REA, almost all subjects with a significant ear advantage have an REA. Furthermore, Zatorre (1989) suggested that the finding of a nonsignificant ear advantage also may be psychologically relevant, as a large proportion of the subjects found to have bilateral speech representation exhibit nonsignificant ear advantages. Therefore, it is important to use the appropriate measure of significance in the analysis of dichotic data.

One problem with the dichotic fusion procedure is that it is particularly susceptible to stimulus dominance (Halwes, 1970; Repp, 1977). For example, if the stimulus pair *coat/goat* is presented an equal number of times to each ear, and the subject's response is always *coat*, then *coat* is considered to be the dominant stimulus. Trials that are subject to stimulus dominance are necessarily uninformative about ear dominance. This generally introduces noise into the data, making it more difficult to obtain a significant ear advantage. It is also possible that there are individual differences in stimulus dominance. Because any laterality index for an individual subject is a combination of ear dominance and stimulus dominance, interpretation of the laterality index is extremely difficult so long as the two variables are confounded, and any comparisons between individuals' degree of lateralization is questionable. What is needed is a method of separating stimulus dominance from ear dominance and producing a laterality index that is a pure measure of the ear advantage. It is possible that the use of a "clean" measure of the ear advantage may be more successful in classifying subjects into left, right, and bilateral language groups.

Methods of Controlling for Stimulus Dominance

The stimulus dominance problem was first identified by Halwes (1970), and several attempts have been made to control its effects. Repp (1977) proposed a solution that partially dealt with the problem of stimulus dominance. The response data for a fused words test can be tabulated as in Figure 1. A 2 × 2 table of stimulus arrangement and stimulus response is prepared for each stimulus pair. The dominant stimulus appears in the left-hand column, and right-ear responses appear along the negative diagonal. It is impossible to determine if responses to the dominant stimulus reflect an ear advantage or a stimulus advantage, so they are discarded. A laterality index (e_i) is computed for each stimulus pair on the basis of only the proportion of right-ear (PR) and left-ear (PL) responses to the nondominant stimulus (in the right-hand column): $e_i = (\text{PR} - \text{PL})/(\text{PR} + \text{PL})$. In the example in Figure 1, the e_i index would be $(4 - 1)/(4 + 1)$, or 0.60. To obtain a laterality index for the whole test, the e_i values for each stimulus pair are averaged to produce a total e. Because e_i becomes unreliable at high levels of stimulus dominance, Repp suggested that each e_i be weighted by a factor of $(\text{PR} + \text{PL})/2$ to attribute greater weight to the more reliable indices. Repp provided the following computational formulas for the calculation of e (Equation 1) and the standard error of e (Equation 2) for a complete test:

$$e = \frac{\Sigma(\text{R} - \text{L})}{\Sigma(\text{R} + \text{L})}, \tag{1}$$

$$se = \left\{ \frac{\Sigma[(\text{R} - \text{L})^2/(\text{R} + \text{L})]}{\Sigma(\text{R} + \text{L})} - \left[\frac{\Sigma(\text{R} - \text{L})}{\Sigma(\text{R} + \text{L})} \right]^2 \right\}^{1/2}, \tag{2}$$

and

$$z(e) = \frac{e}{se}. \tag{3}$$

If one assumes that e is normally distributed, one can perform a significance test of an individual ear advantage using the standard error (*SE*) of the e_i values (Equation 3). Values greater than 1.96 reflect significant REAs (at the .05

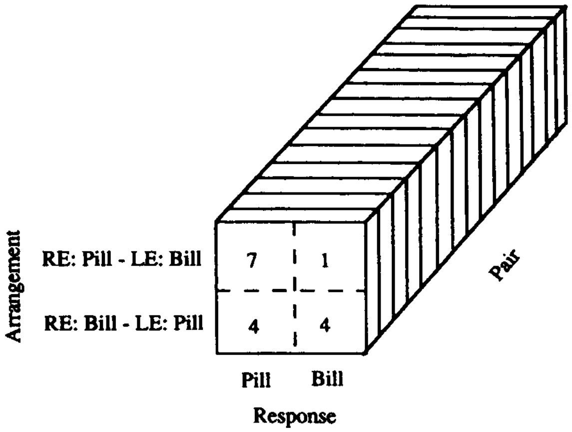

Figure 1. Tabulation of sample response data for a fused dichotic words test in a three-way table. The dominant stimulus appears in the left column, and right-ear responses appear along the negative diagonal. (RE = right ear; LE = left ear.)

level), and values less than −1.96 reflect significant LEAs. There are two problems with this method, however. The first is that, as Repp acknowledged, the reliability of e_i decreases as stimulus dominance increases. More seriously, only responses to the nondominant stimulus are used in the calculation of the ear advantage. Any information about ear dominance obtained from the dominant stimulus is discarded, and the power of any statistical test of the ear advantage is greatly reduced, making a truly significant difference more difficult to detect.

Another method of dealing with stimulus dominance has been developed by Halwes (1991), and variations of it have appeared in the literature (e.g., Murray & McLaren, 1990; Wexler & Halwes, 1983). This method is used to determine what proportion of trials should be attributed to stimulus dominance and ear dominance, respectively. In addition, the trials due to symmetry (neither stimulus dominance nor ear dominance) are discarded. For example, in the table in Figure 1, responses to the nondominant stimulus from the nondominant ear (the upper right quadrant) are due to symmetry, so one response is discarded from each cell. The remaining 12 responses must be attributed to either stimulus dominance or ear dominance. Examination of the left column reveals that 3 out of 9 trials should be attributed to stimulus dominance, because one third of the responses to the dominant stimulus occurred in the nondominant ear (lower left quadrant). Therefore, two thirds of the remaining 12 responses (8) are attributed to the dominant (right) ear. No responses are attributed to the nondominant (left) ear. The same procedure is applied to each stimulus pair to yield revised right- and left-ear scores.

Zatorre (1989) used a slightly different method to discard trials due to stimulus dominance and did not discard trials due to symmetry. The dominant stimulus and the dominant ear are first determined for each stimulus pair. Responses to the dominant stimulus in the nondominant ear are due to stimulus dominance and so are discarded. An equal number of trials are discarded from the responses to the dominant stimulus in the dominant ear. All responses to the nondominant stimulus are scored. In the example in Figure 1, *pill* is the dominant stimulus. The four responses to *pill* in the left (nondominant) ear are discarded (the lower left quadrant), and an equal number are discarded from the right (dominant) ear (the upper left quadrant). All other responses are scored. Thus, seven responses are attributed to the right ear, and one response is attributed to the left ear.

The error in these techniques is in the method of discarding trials. The selection of the stimulus from either the right or left ear is a random event, much like tossing a coin (it turns out that the coin is biased, but that is the hypothesis to be tested). For any event that has a probability of .5, in a series of $2n$ trials, n will be in one category and n in the other only over the very long term. Over the short term and particularly for the few trials under consideration, the actual number falling in each category will have only a mean of n and will be randomly distributed around n in a binomial distribution. The subtraction of a fixed constant (the number of symmetrical trials or the number of stimulus dominant trials) from both right- and left-ear scores disregards the fact that the ear to which the subject responds is random. A further analogy to the coin toss may be useful. If a coin is tossed 50 times, and it lands heads 30 times and tails 20 times, a binomial test reveals the coin to be unbiased. However, if one discards from each cell the number of trials in which the coin fell on its nondominant side (the 20 tails), one is left with 10 heads and 0 tails—a difference that is highly significant by a binomial test. Effectively, one is claiming that the coin is unbiased on 40 trials but biased on 10. This results in an extremely liberal test of significance that is not statistically justified. Halwes's method errs further in its a priori assumption that there is a dominant ear. All trials that are not due to stimulus dominance or symmetry are attributed to the dominant ear, further inflating the statistical test of the ear advantage.

Log-Linear Analysis

We propose that the statistically appropriate method of controlling for stimulus dominance is a conventional log-linear analysis of the response data (for a review of log-linear modelling, see Knoke & Burke, 1980). Log-linear analysis is similar to an analysis of variance, except that models are fitted to predict cell frequencies rather than cell means. Alternatively, the log-linear analysis can be thought of as a chi-square analysis in more than two dimensions. The data from a fused dichotic words test (or any single-response dichotic test) can be represented in a three-way table (Word Pairs × Stimulus Arrangements × Responses; see Figure 1). In this log-linear analysis, main effects reflect imbalances in the marginals; for example, a main effect of response indicates that subjects responded more frequently to the response in the left column than to the response in the right column. Such an effect is likely to occur if we maintain our convention of tabulating the dominant stimulus in the left column. This effect reflects stimulus dominance. Interactions in a log-linear model reflect statistical dependence of two variables. An interaction between response and arrangement means that the response a subject makes is dependent on which stimulus was presented to which ear. Such an effect would be a measure of ear dominance. An interaction between pair and response means that the extent of stimulus dominance differs among word pairs. Following the analogy to analysis of variance, one is able to evaluate interactions independently of main effects. Thus, one can obtain a measure of ear dominance that is independent of stimulus dominance.

To test effects in log-linear analysis, one fits a series of log-linear models. Each model yields a likelihood ratio chi-square value, which is a measure of goodness of fit (actually, it is a measure of poorness of fit; high chi-square values indicate that the model does not provide a good fit to the data). To test the Response × Arrangement interaction (ear dominance), one first fits a model that includes all relevant effects except the interaction of interest (main effects of pair, response, arrangement, the Pair × Response interaction, and the Pair × Arrangement interaction) and notes the likelihood ratio chi-square value for the model.

One then fits a second model that includes all effects in the first model plus the Response × Arrangement interaction. If the interaction is significant, the second model will provide a better fit to the data than the first; that is, the change in likelihood ratio chi-square values, evaluated at the change in degrees of freedom for the two models, will be significant.

The log-linear analysis will also provide a measure of the degree of lateralization. A series of parameter estimates (λs) are produced for each effect. The parameter for the Response × Arrangement interaction (which we call λ^*) is analogous to Bryden and Sprott's (1981) λ index: It is the log-odds ratio of right-ear responses to left-ear responses after stimulus dominance has been statistically controlled. Negative values indicate LEAs, and positive values indicate REAs. λ^* also has a standard error associated with it (σ_{λ^*}), so that $z(\lambda^*)$ can be calculated according to Equation 4.

$$z(\lambda^*) = \frac{\lambda^*}{\sigma_{\lambda^*}} \tag{4}$$

As $z(\lambda^*)$ is approximately normally distributed, its significance is easily determined from standard normal tables. The values for $z(\lambda^*)$ range from negative infinity (an LEA) to positive infinity (an REA). Like λ, λ^* is not constrained by accuracy. Many common statistical software packages will produce likelihood ratio chi-square values, λ parameters, and standard errors for each model.[2]

Log-linear modelling lends itself well to the single-response fused words technique. However, dichotic fusion and stimulus dominance are also apparent in the commonly used CV pairs procedure when only one response is given. With the proper counterbalancing, so that each CV combination can be considered a stimulus pair, and a sufficient number of trials, individual response data could be tabulated as in Figure 1, and a log-linear analysis performed.

To improve on a conventional analysis and justify the extensive calculations involved, the method must meet two criteria: First, it must produce an index of ear dominance that is independent of stimulus dominance. The analysis meets the first criterion on purely statistical grounds. Second, a greater proportion of subjects should be classified as having a significant ear advantage than with current acceptable methods (λ or e). To determine the method's usefulness in the classification of ear advantage, we administered the Fused Dichotic Words Test (Halwes, 1991) to a sample of 104 right-handers and 30 left-handers. Individual subject data were analyzed with a conventional λ index, e, and a full log-linear analysis. Comparisons were made between methods.

Method

Subjects

Forty-three of the subjects (18 right-handed boys, 3 left-handed boys, 18 right-handed girls, and 4 left-handed girls) were 10-year-old school children recruited through the Waterloo County Board of Education. The remaining 91 subjects (34 right-handed men, 11 left-handed men, 34 right-handed women, and 12 left-handed women) were undergraduate students from the University of Waterloo. A total of 104 right-handers and 30 left-handers were assessed.

Procedure

The stimulus set was the Fused Dichotic Words Test.[3] The stimuli consisted of 15 pairs of rhyming, CVC words (e.g., *coat/goat*), which had been temporally aligned so as to produce a single percept when presented dichotically. Stimuli were produced on a PDP-2/24 computer and recorded on audiocassette. Each pair of stimuli occurred four times in each of two possible arrangements (Stimulus A to the right ear, Stimulus A to the left ear), for a total of 120 trials per randomization, arranged in blocks of 30 trials. Two randomizations, or a total of 240 trials, were presented. Stimuli were played back on a Sony Walkman Professional (WM-D6C), through Telephonics TDH-39 acoustically matched headphones with circumaural cushions. Earphones were reversed after the first, third, fifth, and seventh blocks to control for mechanical effects. Subjects were told to circle the word they heard on an answer sheet that included the word from the left ear, the word from the right ear, and two rhyming distractors, and were encouraged to guess if they were unsure. Subjects were not told that presentation was actually dichotic.

Results

Three laterality indices were calculated for each subject, λ, e, and λ^*, according to the methods described previously. Each index has a standard error associated with it, and standardized values were used in all subsequent analyses to allow direct comparisons between indices.

The results of individual significance tests and the means and standard deviations of each standardized index are presented in Table 1. A fairly strict significance level of .05 was set. λ^* classified the greatest number of ear advantages as significant, followed by λ and e. When λ^* was used as a laterality index, 98% of significant ear advantages in right-handers were REAs. In left-handers, 73% of significant ear advantages were REAs. When both significant and nonsignificant ear advantages were considered, 95% of right-handed subjects and 65% of left-handed subjects exhibited an REA.

Frequency distributions obtained with each index are presented in Figure 2. In right-handers, both λ and λ^* produced normal distributions with a mean greater than zero, but e produced a skewed distribution, as most values were not significantly different from zero.

The two λ-type measures (λ and λ^*) were highly correlated ($r = .96$ in right-handers and $r = .99$ in left-handers). This suggests that there are not great individual differences in stimulus dominance. Correlations with e were much

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[2] At the time we wrote this article, *SPSSx*, *SAS*, and *BMDP* all performed log-linear analysis and produced the appropriate parameter estimates. *Systat* produces likelihood ratio chi-square values for each model but does not produce the parameter estimates. Information on how to perform the analysis with each of these software packages is available from Gina M. Grimshaw.

[3] The Fused Dichotic Words Test was obtained from T. Halwes at Precision Neurometrics, 108 Everit Street, New Haven, CT 06511.

Table 1
Standardized Laterality Indices and Classification of Ear Advantages in Right-Handers (n = 104) and Left-Handers (n = 30)

Group	*M*	*SD*	Significant LEA *n*	Significant LEA %	Nonsignificant LEA *n*	Nonsignificant LEA %	Nonsignificant REA *n*	Nonsignificant REA %	Significant REA *n*	Significant REA %
Right-handers										
$z(\lambda)$	2.57	2.03	0	0	6	6	44	42	54	52
$z(\lambda^*)$	2.56	2.06	1	1	4	4	39	37	60	58
$z(e)$	1.56	1.80	0	0	3	3	75	72	26	25
Left-handers										
$z(\lambda)$	0.72	2.21	4	13	7	23	10	33	9	30
$z(\lambda^*)$	0.69	2.37	4	13	7	23	8	27	11	37
$z(e)$	1.66	6.10	1	3	7	23	17	57	5	16

Note. LEA = left-ear advantage; REA = right-ear advantage.

smaller (they ranged from .37 to .77) but remained statistically significant.

Discussion

In this article, we have proposed a laterality index (λ*) that controls for stimulus dominance effects and provides a significance test for each subject. Methods that discard trials due to stimulus dominance, such as those used by Halwes (1991) or Zatorre (1989), are inappropriate because they disregard the probabilistic nature of the data. Empirically, we found that this method has clear advantages over the *e* index. The *e* index found only 25% of our right-handed subjects to have a significant REA, whereas λ* found 58% of right-handers to have a significant REA. This is most likely because the use of only responses to the nondominant stimulus greatly reduced the power of any test of the ear advantage. The *e* index was also poorly correlated with λ* and is fairly laborious to calculate.

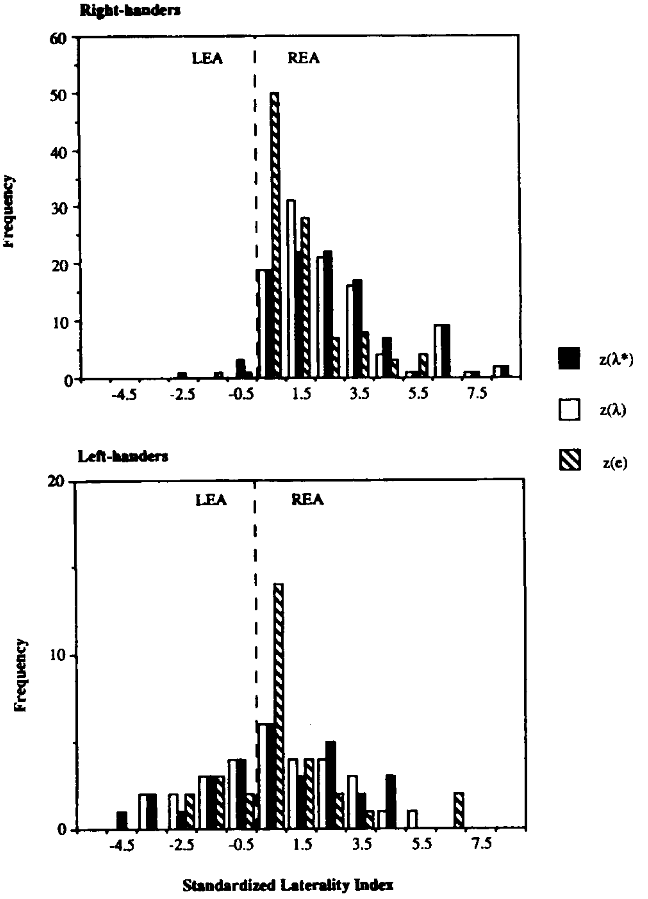

Figure 2. Frequency distributions of three laterality indices in right-handers and left-handers. (LEA = left-ear advantage; REA = right-ear advantage.)

The distinction between λ* and a conventional λ index is less clear. The λ index found 52% of right-handed subjects to have a significant REA, compared with 58% as determined by λ*. Furthermore, the two indices were highly correlated with each other. This suggests that very small (if any) individual differences are observed in stimulus dominance. The distributions of each index were clearly different for left- and right-handers. If one's goal in the analysis of dichotic data is an assessment of the significance of the ear advantage, then λ* has a slight advantage over λ. For instance, because it is a purer measure of ear dominance, λ* may more effectively distinguish between individuals with left- versus bilateral language representation. However, if one is not concerned with the statistical significance of the ear advantage, λ may provide a good approximation to λ* and is certainly easier to calculate.

There is some question as to what significance level one should use when assessing an ear advantage, and again, the solution depends on the goals of the experimenter. By setting a fairly strict significance criterion (e.g., $p < .05$), one reduces the number of subjects with no ear advantage (NEA) who are misclassified as having REAs. This may be desirable if one wants to produce a homogeneous group of subjects with REAs or to determine the direction of the ear advantage for clinical reasons. However, when a strict criterion is used, the number of true REAs who are misclassified as NEAs will increase. This is of course the trade-off between Type I and Type II errors in significance testing. As Zatorre (1989) suggested, truly nonsignificant ear advantages may be meaningful as well, as they may reflect bilateral language representation. It may be desirable to test if ear advantages are significantly zero (by setting α equal to .95 and failing to reject the null hypothesis unless p is greater than α). It is possible that use of this index to analyze data in large populations of left-handers (much larger than that included here) will yield a trimodal distribution of ear advantages (McManus, 1983). Ideally, the optimal significance level to minimize misclassification will be based on studies of individuals for whom side of speech lateralization is known.

A final note concerns our general findings with the Fused Dichotic Words Test. If the direction of ear asymmetry is examined regardless of its degree or statistical significance, we find that 95% of right-handed subjects and 65% of left-handed subjects have an REA for the identification of fused words. Note that these proportions are very similar across laterality indices, as stimulus dominance will affect the degree of lateralization but not its direction. These values correspond closely to those observed in clinical samples (Segalowitz & Bryden, 1983) and support the validity of the Fused Dichotic Words Test. We propose that the dichotic fusion technique, paired with the analysis described in this article, is the best method currently available for the noninvasive assessment of language lateralization.

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