INDICES OF HEMISPHERIC LATERALIZATION: A METHODOLOGICAL ANALYSIS*

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ABSTRACT

This paper discusses an important methodological problem in cerebral asymmetry research, that of the use of indices of hemispheric lateralization. Studies in this field have examined dependent variables such as accuracy of response, reaction time, and electrophysiological measures and have frequently attempted the comparison between subjects or groups of subjects of the degree of lateralization of various perceptual and cognitive capabilities. Some measure of hemispheric lateralization - a numerical index derived from the experimental data - is employed in making these comparisons. A variety of difference, ratio, and compound indices of lateralization have been proposed and applied in the literature. Here, these indices are described and critically evaluated. The use of laterality indices as ordinal vs. ratio measures is discussed. An index-free ranking procedure for making comparisons of degree of lateralization is then described which makes the fewest theoretical assumptions. Finally, detailed consideration is given to the assumptions involved in indexing hemispheric lateralization from EEG alpha asymmetry data. Extensions of the index-free ranking procedure to this approach are described.

I. INTRODUCTION - THE CONCEPT OF HEMISPHERIC SPECIALIZATION; INVESTIGATIVE APPROACHES

Early brain lesion studies, as well as more recent data from commissurotomy patients, suggested that fundamental functional differences exist between the cerebral hemispheres of man. The left hemisphere appeared to be specialized for language; the right for visuo-spatial processes.

The dramatic nature of the results of hemispheric specialization research and the seductive appeal of the left-right dichotomy opened the door to over-simplification and misrepresentation. The left cerebral cortex was popularized as the "dominant" hemisphere, as verbal, and responsible for logical-analytic thought. By contrast, the right hemisphere emerged as the "minor" hemisphere, as nonverbal, spatial, intuitive, holistic, and the seat of emotion. Speculation flourished.

A more responsible view looks upon hemispheric specialization as much more fluid and less clear-cut. The existence of certain linguistic capabilities of the right hemisphere (Zaidel, 1978a), for example, demonstrates that the strict concept of lateralization is oversimplified. Few higher functions can be localized to just one hemisphere; rather, both hemispheres possess capacities for all types of processing. Hemispheric specialization appears to be a matter of degree (Zangwill, 1960), with lateralization a continuous variable reflecting the differential involvement of two interacting hemispheres.

Before taking up the central question of how the degree of lateralization is quantified, the main experimental techniques employed in investigating hemispheric specialization are reviewed.

While studies of lesion and split-brain patients continue, the bulk of hemispheric specialization research today is concerned with laterality effects in normal subjects. The experimental techniques used to elicit these effects fall into three general categories:

Clinical approaches include the Wada test, the regional cerebral blood flow technique, unilateral electroconvulsive shock therapy, and electrical stimulation during neurosurgery. In the Wada test (Branch et al., 1964), sodium amobarbital is injected into the carotid artery on one side. Shortly thereafter, the activity of the ipsilateral hemisphere is greatly reduced and for a period of several minutes the isolated opposite hemisphere can be tested. The regional cerebral blood flow technique (Ingvar and Lassen, 1977) involves the inhalation of radioactive Xenon-133 gas and allows real time monitoring of localized cerebral metabolic activity in the conscious subject. Observations of transient cognitive deficit following lateralized electroconvulsive shock therapy (Cohen et al., 1973) in psychiatric patients have yielded some data. The results of electrical stimulation of various parts of the exposed cortex of conscious patients during surgery have been recorded by Penfield (1958) and are also relevant. These procedures possess varying degrees of risk and are restricted to clinical populations. Their usefulness in hemispheric specialization research is correspondingly limited.

Lateralized sensory input paradigms are in widespread use and involve the presentation of stimuli in such a manner that the principle projection is confined to a single hemisphere. The underlying assumption in this approach is that processing will be faster and/or more accurate if information is projected directly to the hemisphere specialized for the task and need not cross via the corpus callosum to be utilized. Thus in dichotic listening studies each ear receives concurrent and different input under which conditions the contralateral auditory projection dominates. Similarly, tactile input to one hand projects to the contralateral hemisphere. Tachistoscopic presentation (to prevent saccadic eye scanning) of visual information to one visual hemifield allows restriction of direct input to the contralateral striate cortex. In these lateralized sensory input studies some measure such as reaction time or accuracy is obtained separately for left and right hemisphere trials.

Finally, electrophysiological techniques (Desmedt, 1977) employ scalp electrodes to measure gross electrical brain activity over the hemispheres. The ongoing EEG can be sampled and hemispheric differences in alpha level, for example, can be assessed. The assumption is made here that alpha level and cognitive activity are inversely related. Evoked potential studies typically look at differences in peak amplitude and latency at homologous left-right recording sites. Electrophysiological approaches have the advantage of providing a noninvasive measure of hemispheric activity in the normal, behaving subject.

II. THE PROBLEM OF SELECTING AN INDEX OF LATERALIZATION

Assuming that hemispheric specialization is a continuous variable, the problem remains as to how the degree of lateralization is to be quantified. This problem arises when comparisons of hemispheric specialization are attempted. The questions asked in cerebral asymmetry studies typically take one of two forms:

1) Are members of group X more right (or left) lateralized than members of group Y for function A?
2) Is function A more right (or left) lateralized than function B in members of group X?
3) Are members of group X more right (or left) lateralized for function A under conditions P or S?

Groups X and Y might be: males, females, right-handed individuals, left-handed individuals, 4-year olds, university undergraduates, artists, the general population, etc. Functions A and B might be: recognition of faces, detection of target words, embedded figure recognition, etc. Conditions P and S might be: varying social environment, drug induced or hypnotic states, attentional variables, etc.

Most studies attempt to answer such questions by quantifying the degree of lateralization of the function in question for each group. An experiment is performed, asymmetry data collected, and from these data a numerical index of lateralization is derived. This index forms the basis for inferences about the relative degree of lateralization in comparisons. The problem is how to go from experimental data to index.

Stated in formal terms, let (L_1,R_1) and (L_2,R_2) represent the experimental data from two subjects or groups with L being the score associated with the left hemisphere trials and R the corresponding right hemisphere score. Then an index of lateralization f is a function which maps the space of experimental data into the real numbers such that: group (or subject) 1 is greater right (or left) lateralized than group (or subject) 2 if and only if $f(L_1,R_1) > f(L_2,R_2)$.

In general, there are an infinite number of such indices. The problem of selecting the appropriate index of lateralization is nontrivial; this can be appreciated by taking note of the fact that what is attempted here is an ordering (in one dimension) of data points which are ordered pairs (elements of a two-dimensional space). The decision on how this is done (the selection of an index) can affect the conclusions arrived at concerning degree of hemispheric lateralization.

III. EVALUATION OF INDICES

The experimental data resulting from the various hemispheric specialization research paradigms are of several kinds. Examples include: percentage of correct responses (Kimura, 1961) on trials believed to involve the right hemisphere, reaction time (Hellige, 1975) for tasks believed to require the right hemisphere, intensity of stimulus input (Cullen et al., 1974) to the right hemisphere to achieve some predetermined performance level, relative spectral power in the alpha band of the EEG (Perlaki and Barchas, 1983) recorded from a right hemisphere site, and corresponding measures for the left hemisphere. In this section the only laterality indices considered are those derived from experimental data of the percent-correct response type. The essential aspects of the corresponding indices for the other types of data are analogous to those described below.

Let R represent the proportion of correct responses for experimental trials assumed to involve the right hemisphere. Suppose R is normalized so that $0 \leq R \leq 1$. Let L be the corresponding datum for the left hemisphere trials. The simple difference measure $d = R - L$ has been used as an index of lateralization in a number of studies. The numerical value of d ranges between 1.0 representing the maximal degree of right lateralization, to -1.0 representing maximal left lateralization.

A geometrical representation of d is useful. The experimental data space of all possible pairs (R,L) is the unit square; the locus of all points which are assigned the same fixed value of d are line segments parallel to the main diagonal. Figure 1 shows these isolaterality contours.

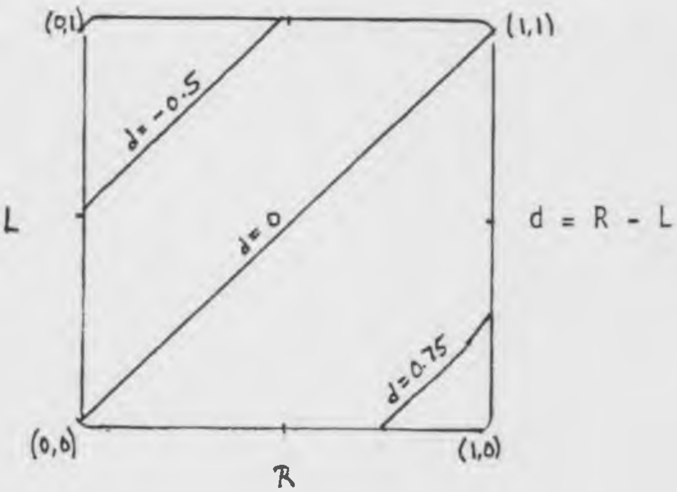
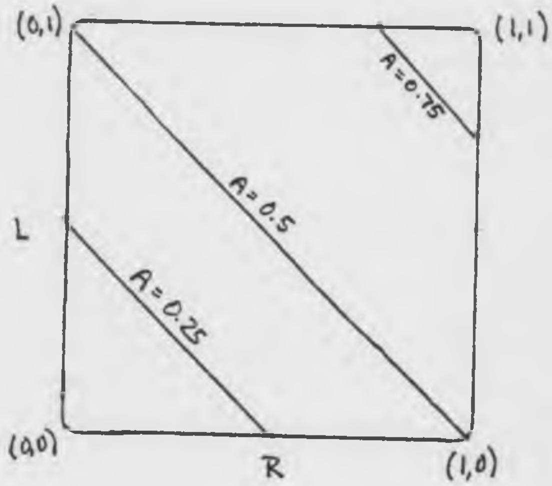


Figure 1.

While d may be useful as a statistic in determining the existence of lateralization, it has a fundamental drawback in its utility as an index for making comparisons of the degree of lateralization. This is illustrated in Kimura's (1963) study of the development of lateralization in a dichotic listening task. There, the degree of lateralization, as indexed by d, decreased between the ages 4 and 9. A review of the data from the study reveals the reason for this surprising result: older children made very few errors and could only obtain small values of d. Younger children made many more errors and could therefore achieve much larger difference scores.

It is thus clear that d is unlikely to be an appropriate index of lateralization. The reason is that the range of d is constrained by the level of accuracy. To graphically portray what this means, define $A = \frac{1}{2}(R + L)$ as "total accuracy." Figure 2 shows curves of equivalent total accuracy in the experimental data space.



$A = \frac{1}{2}(R + L)$

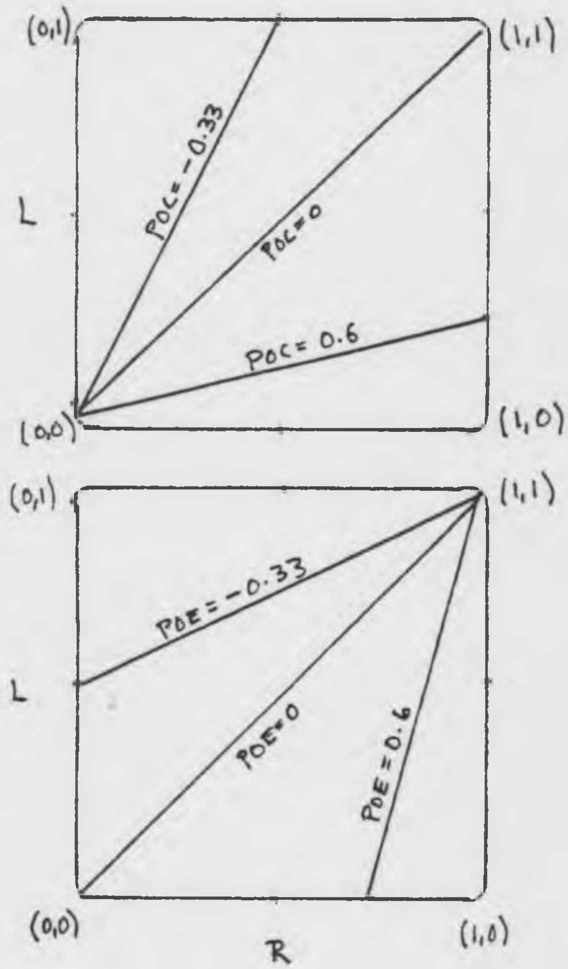
Figure 2.

An examination of Figure 1 together with Figure 2 reveals that at low and high levels of total accuracy the range of values that d can take on is restricted. Only for values of A = 0.5 can d possibly assume its minimum and maximum values. This is the shortcoming that makes d = R - L unsuitable as an index of lateralization.

In an attempt to correct for the limitations of d, Harshman and Krashen (1972) suggested the two indices POC and POE defined by

$$POC = \frac{R - L}{R + L} \qquad POE = \frac{R - L}{2 - R - L}$$

POC measures the right-left difference as the proportion of total correct responses; POE represents the right-left difference as a proportion of total errors. Like d, POC and POE may take on values from 1.0 (maximal right lateralization) to -1.0 (maximal left lateralization). Isolaterality contours for POC and POE appear in Figure 3.



$$POC = \frac{R - L}{R + L}$$

$$POE = \frac{R - L}{2 - R - L}$$

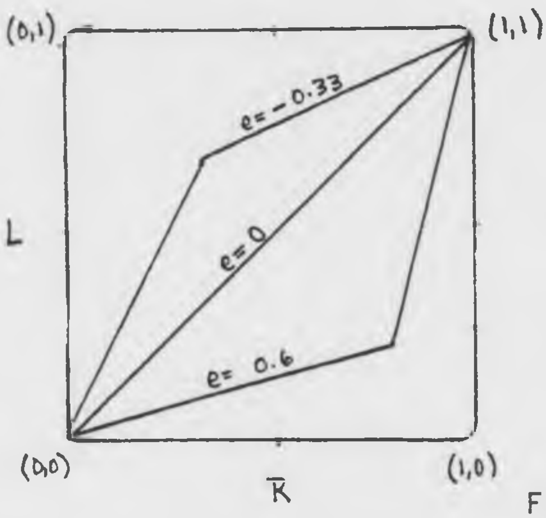
Figure 3.

For values of total accuracy less than 0.5 the laterality index POC is not constrained by total accuracy, i.e., for $0 \le A \le 0.5$ POC can assume any value in its entire range of 1.0 to -1.0. Similarly, the range of the index POE is independent of total accuracy level for $0.5 \le A \le 1.0$. Harshman and Krashen advocated POE as an index of lateralization after finding POC to be significantly negatively correlated with total accuracy in a large number of dichotic listening experiments from the literature, but POE showing only a slight positive correlation. But, as Repp (1977) notes, this result can be explained by the fact that total accuracy levels in dichotic listening studies tend to be high, giving data points that fall in the region where POE, but not POC, is unconstrained by accuracy level. Thus, both POC and POE have limitations as a general index of lateralization in being constrained in range at certain levels of total accuracy.

The index e defined by

$$e = \begin{cases} R - L / R + L & \text{if } 0 \le A \le 0.5 \\ R - L / 2 - R - L & \text{if } 0.5 \le A \le 1.0 \end{cases}$$

appears to overcome these difficulties by combining qualities of POC and POE (Halwes, 1969; Marshall, Caplan, and Holmes, 1975). Isolaterality contours for this index appear in Figure 4.



$$e = \begin{cases} R - L / R + L & \text{if } 0 \le A \le 0.5 \\ R - L / 2 - R - L & \text{if } 0.5 \le A \le 1.0 \end{cases}$$

Figure 4.

The laterality index e expresses the observed right-left difference as a fraction of the maximal possible difference at the given level of total accuracy. Its range is therefore independent of total accuracy; at any accuracy level e may take on any value between 1.0 and -1.0. This measure has been advocated as the optimal index of lateralization by a number of authors.

The laterality indices described above are only four of the infinite number of possible indices that can be defined on the experimental data space. It must be realized that each such index represents a specification of the relationship between the observable surface measures and the underlying neurophysiological lateralization. At present, there has developed little theoretical or empirical basis for suggesting any particular relationship, thus as Richardson (1976) has argued, the choice of laterality indices is arbitrary.

Consider, for example, the quality of unconstrained range over accuracy levels which the index e achieves. Independence from accuracy level is ostensibly a desirable quality for a laterality index since it presumedly allows comparison of subjects of different levels of performance. However, there is no *a priori* reason to believe that hemispheric lateralization should be independent of accuracy. The right hemisphere may be inherently less accurate than the left (Zaidel, 1978b). Indeed, Birkett (1977) found that each of the laterality indices d, POC, POE, and e was significantly correlated with total accuracy in a tachistoscopic visual lateralization task and suggested this might reflect psychological processes rather than statistical bias. With the relationship between total accuracy and degree of lateralization undetermined, the selection of one index over another cannot be logically upheld.

In Section V a procedure for making comparisons of degree of lateralization is described which makes much weaker theoretical assumptions.

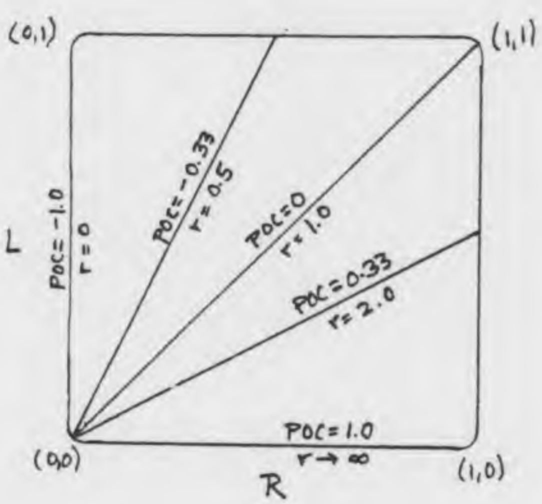
IV. LATERALITY INDICES AS ORDINAL VS. RATIO MEASURES.

In this section, a brief digression is made from the topic of the problems of selecting an index of lateralization to discuss a separate but very important methodological problem: the use of laterality indices as ordinal vs. ratio measures.

There are two ways that an index of lateralization might be used in making comparisons of degree of lateralization. The numerical values which the index assigns to each experimental data point may be used to <u>rank</u> the set of data points. Once this ordering is complete, the index has served its purpose and is disregarded in the subsequent analysis. Nonparametric statistical tests can then be applied to the ranked data points to assess group differences in degree of lateralization. In this approach, the laterality index is only used as an <u>ordinal</u> measure.

A second method, which has been used in some studies, is to use the numerical value of the index as a variable in the statistical analysis. This use of a laterality index as a <u>ratio</u> measure makes the much stronger assumption that the numerical magnitude of the index has some physical meaning.

To illustrate the problems inherent in this approach it is useful to make a comparison of the laterality indices POC and the ratio r = R/L. The set of isolaterality contours for each of these indices is identical. The numerical value that each index assigns to the contours, however, is not the same. This is illustrated in Figure 5.



$$POC = \frac{R - L}{R + L}$$

$$r = \frac{R}{L}$$

Figure 5

Along any line of constant total accuracy POC takes on all values in its range of -1.0 (maximal left lateralization), through 0 (no lateralization), to 1.0 (maximal right lateralization). The index r, however, varies from 0 (maximal left lateralization), towards + OO (maximal right lateralization), with 1.0 representing equilaterality.

Both indices ordinally rank a set of experimental data points exactly the same. This follows from the algebraic fact that

$$\frac{a_1}{b_1} > \frac{a_2}{b_2} \text{ if and only if } \frac{a_1-b_1}{a_1+b_1} > \frac{a_2-b_2}{a_2+b_2} \text{ for all } a_1, b_1, a_2, b_2 > 0$$

and is manifested in the coincidence of isolaterality contours for the two indices. The numerical values the indices assign to data points, however, are quite different. Hence, the results obtained when the magnitudes of the indices are used in statistical tests (t-tests, F-tests, correlations) will be different.

The question is: Which index should be used? The problem of selection is compounded by the fact that POC and r are just two members of an infinite set of indices each of which 1) has an identical set of isolaterality contours, and 2) ranks a fixed set of data points in exactly the same order, but 3) assigns different numerical values to these data points. (For example

$\lambda_a = \dfrac{R^a - L^a}{R^a + L^a}$ where a is any fixed nonzero real number, defines an infinite subclass of this set).

In the previous section it was noted that, in the absence of sufficient knowledge of the relationship between the experimental measures and the underlying cerebral lateralization, the selection of one type of index over another is arbitrary. The above demonstrates that even once an index with a particular set of isolaterality contours (and hence particular ordinal ranking properties) has been decided upon, the assignment of meaningful numerical values to the index to allow its use as a ratio measure is even more problematic. Given the current knowledge of the relation between surface asymmetries and underlying lateralization, the use of the numerical value of indices derived from the data as variables in statistical analysis (i.e., as ratio measures) cannot be justified; only their use as ordinal measures is recommended.

V. AN INDEX-FREE RANKING PROCEDURE

Richardson (1976) has proposed the following index-free ranking procedure for making comparisons of degree of lateralization. Suppose (L_1, R_1) and (L_2, R_2) are left and right hemisphere experimental data from subject 1 and subject 2. Then subject 1 is greater left lateralized than subject 2 if and only if

$$L_1 > L_2 \text{ and } R_1 < R_2$$

This is a transitive order and so allows a ranking of subjects according to their degree of lateralization. The Mann-Whitney U Test, a nonparametric statistical test, can then be used to determine the statistical significance of a group difference in degree of lateralization.

Clearly, however, the ordering is incomplete, i.e, there may exist pairs of data points which cannot be ranked. If $L_1 > L_2$ and $R_1 > R_2$, or if $L_1 < L_2$ and $R_1 < R_2$ then the matter is undecided; the degree of lateralization of these pairs is noncomparable.

A geometrical illustration is given in Figure 6 in which the set of experimental data points assigned a greater degree (dotted) of left lateralization and those assigned a lesser degree (striped) of left lateralization than a representative point (L_0, R_0) for each of the indices d, POC, POE, e and the index-free ranking procedure are designated.

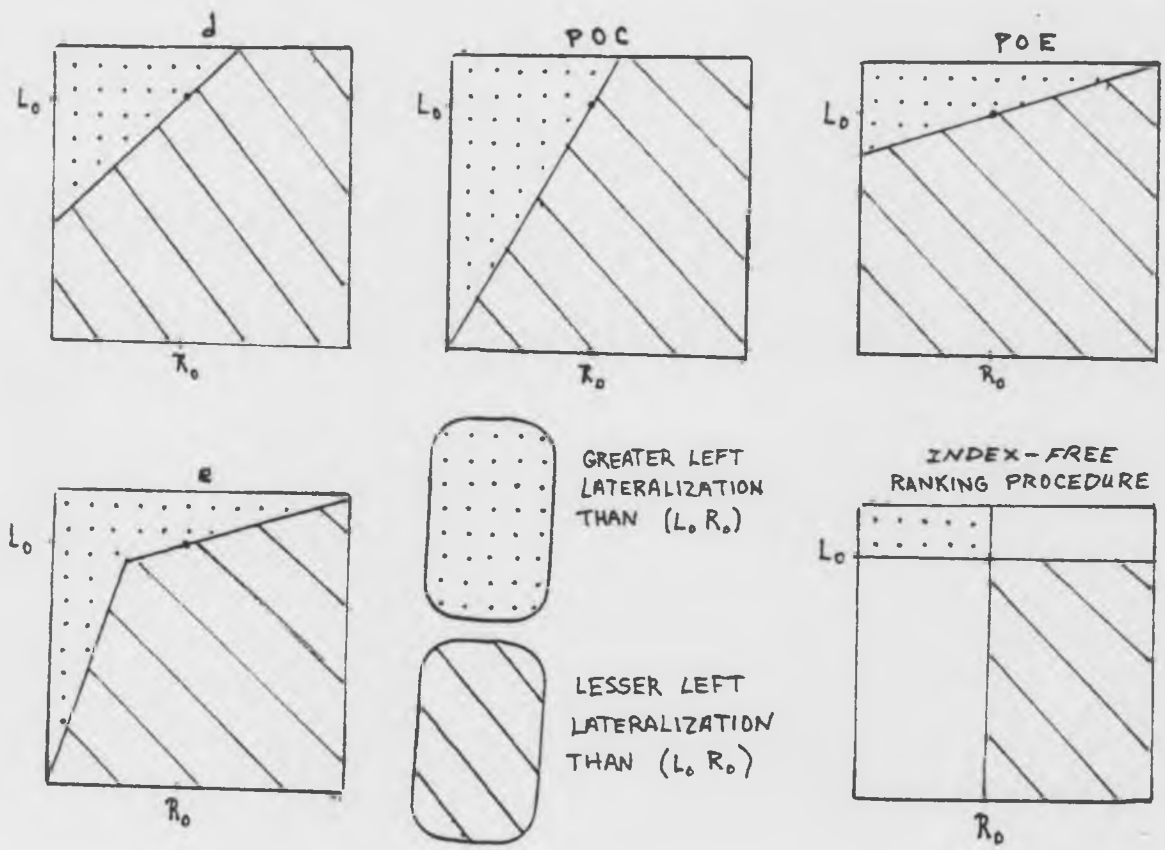


Figure 6.

The attraction of the index-free ranking procedure for making comparisons of degree of lateralization is its parsimony. The only thing that is assumed is a monotonic correspondence between the underlying cerebral lateralization and the experimental measures. No numerical scale is imposed, nor are any assumptions made about the relationship with accuracy level.

The drawback of the index-free ranking procedure is its restricted range of applicability. The fact that many, possibly most, of the experimental data points from a study may be noncomparable under the procedure is clearly a serious disadvantage.

The index-free ranking procedure is a very conservative means for making comparisons of the degree of lateralization. The cost of its economy of assumptions is its restricted practical usefulness. Nevertheless, in the absence of a theory relating underlying cerebral asymmetry to experimental surface measures, and with the present lack of rigor characterizing much of hemispheric specialization research, this may be a price that must be paid.

VI. LATERALITY INDICES DERIVED FROM EEG ALPHA ASYMMETRIES

In this section the problem of making comparisons of degree of lateralization based on right/left asymmetries in EEG alpha wave activity is discussed. First, the nature of the problem is described. Then, three approaches to interpreting alpha asymmetries as measures of hemispheric lateralization are discussed. The assumptions underlying each of these interpretations are set forth, laterality indices for each are critically evaluated, and appropriate extensions of the index-free ranking procedure are given.

In using differences in EEG alpha activity as indicators of hemispheric lateralization of higher functions in man, an assumption is usually made associating a decrease in alpha activity with an increase in cognitive processing. Differences in suppression of alpha activity between the right and left sides during an experimental task are thought to reflect differential hemispheric involvement. Since the task-induced alpha suppression may be superimposed upon a pre-existing alpha asymmetry, comparisons are often made to a baseline measure recorded during a resting state before the experimental task. Thus, in general, the experimental data from a given individual for a given task take the form (L,R,BL,BR) where L represents the alpha activity recorded over the left hemisphere during the task, BL the left side baseline alpha activity, and with R and BR the coresponding measures from the right side. It is from data of this form that comparisons of degree of lateralization are to be made.

The problems in numerically indexing lateralization from a 4-valued experimental data point are no fewer than those described previously for 2-valued data points. Analogous to the difficulty in making comparisons of individuals with different levels of overall accuracy is the problem of individuals with varying levels of overall alpha activity. An additional and distinct concern is the question of how differences in initial baseline activity are to be dealt with.

Three plausible approaches to solving these problems by specifying how right and left alpha levels and baseline information are to be interpreted as indicators of lateralization are listed below.

1) Disregard baseline data and consider only the alpha levels during the experimental task in making comparisons of degree of lateralization.
2) Consider the magnitude and direction of the shift from baseline on each side as the variables of interest.
3) Consider the shift from baseline in relation to initial baseline activity as the accurate indicator of hemispheric activation on each side.

Each of these approaches entails different general assumptions about the relationship between the underlying cerebral lateralization and the observed measures L, R, BL, and BR. There are, in general, many numerical indices consistent with, though not uniquely specified by, each interpretation. For each approach, index-free ranking procedures can be defined which make the fewest additional assumptions. Below, these matters are discussed for each of the three approaches in turn.

The first approach -- to disregard BL and BR and use only L and R -- derives from the assumption that the levels of alpha activity recorded from the right and left sides during the experimental task accurately reflect hemispheric activation, with lower alpha activity corresponding to greater hemispheric cognitive involvement. A motivation for this approach might be the concern that baseline measures are subject to uncontrollable variations and are thus irrelevant, i.e., that an objective baseline cannot be established.

With the elimination of BL and BR from consideration the problem reduces to that of establishing a laterality index for a 2-valued experimental data point as discussed in previous sections. Included among possible indices are

$R - L$ and $\frac{R - L}{R + L}$, analogous to d and POC, but where a greater value of the index reflects greater left (rather than right) hemisphere involvement. However, such indices suffer from the same problems discussed for d and POC. Each numerical index derived from the EEG alpha levels L and R represents a specification of the relationship between the surface measures and the underlying cerebral asymmetry and requires theoretical justification. And, as before, an index-free ranking procedure provides a means of making comparisons of degree of lateralization without additional assumptions. An index-free ranking procedure for this approach would be defined as:

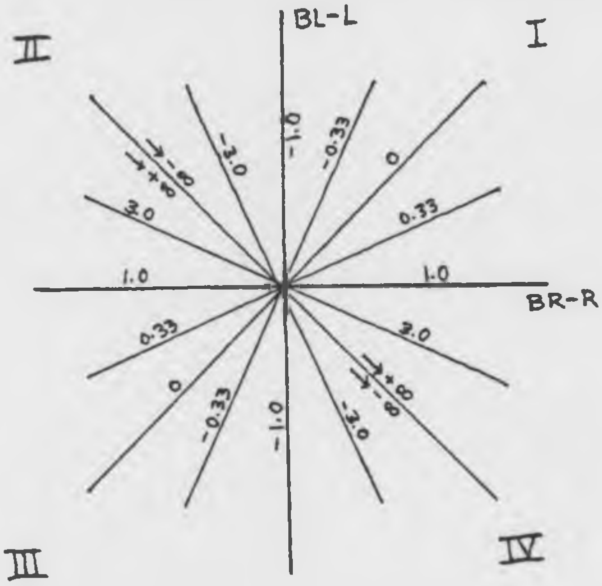
(L_1,R_1,BL_1,BR_1) is greater right lateralized than (L_2,R_2,BL_2,BR_2)
if and only if $L_1 > L_2$ and $R_1 < R_2$

The *second approach* treats the values of the right and left *shifts* from baseline as the appropriate variables for use in making comparisons of degree of lateralization. The assumption here is that the numerical values BL - L and BR - R are accurate indicators of hemispheric activation, with a greater shift corresponding to greater cognitive activation. It is thus assumed that a meaningful baseline can be established. A motivation for this approach might be the concern that an existing hemispheric bias in alpha activity makes direct comparison of the levels of alpha activity during the task (i.e., L and R) inappropriate.

One index consistent with this approach is the simple difference measure D = (BR - R) - (BL - L), analogous to d of Section III. However, it might be argued that this difference should be scaled by the overall shift. One way to do this would be to substitute the values of the right and left baseline shifts for R and L in the index $\frac{R - L}{R + L}$ to obtain

$$l_0 = \frac{(BR - R) - (BL - L)}{(BR - R) + (BL - L)}$$

This measure represents the difference between the right and left baseline shifts as a proportion of the total shift from baseline. However, this index and its variants discussed below, suffer from a problem due to the fact that the shifts from baseline BL - L and BR - R may take on *negative* values (i.e., there may be an increase in alpha activity from baseline during the experimental task). This difficulty can be illustrated geometrically by examining the isolaterality contours of l_0 plotted in the experimental data space of BR - R vs. BL - L as shown in Figure 7.



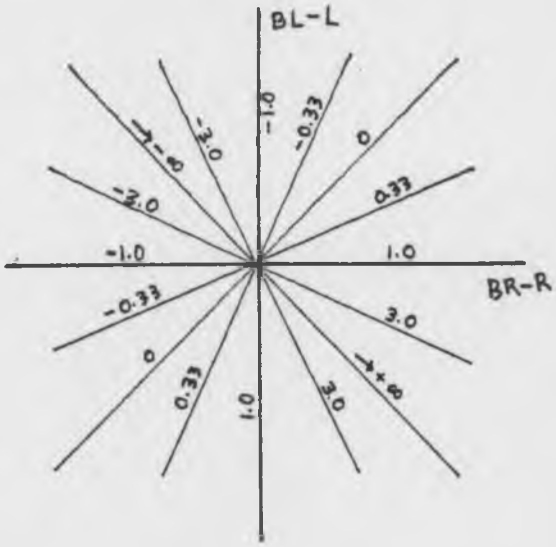
$$l_0 = \frac{(BR - R) - (BL - L)}{(BR - R) + (BL - L)}$$

Figure 7.

In the first quadrant, where BR - R and BL - L are both positive, the behavior of l_0 is acceptable. In quadrants II, III, and IV, however, where one or both of BR - R and BL - L are negative, the difficulty arises. Consider lines on which BL - L is constant; these are lines parallel to the BR - R axis. As one moves to the right in the first quadrant along such a line (i.e., as BR - R increases while BL - L is held constant) the value of l_0 increases as desired. But in quadrant III, and in parts of quadrants II and IV, the opposite occurs: as BR - R increases while BL - L is held constant, the laterality index l_0 decreases. This is inconsistent with the assumption that alpha suppression corresponds to greater hemispheric activation. Moreover l_0 takes on unbounded positive and negative values near to the line BR - R = -(BL - L) in quadrants II and IV. It is clear that l_0 is unsuitable as an index of lateralization for this approach.

Modifications of l_0 can be made to attempt to correct this condition. Isolaterality contours for the index l_1 (Perlaki and

Barchas, 1982) obtained by taking the absolute value of the denominator of 1_0 appear in Figure 8.

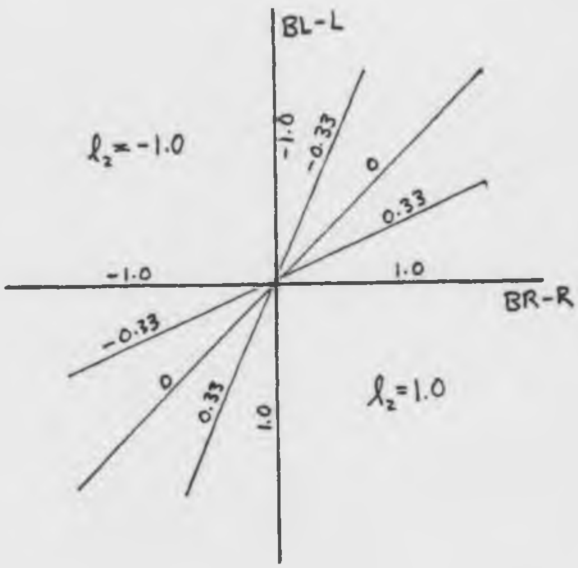


$$1_1 = \frac{(BR - R) - (BL - L)}{|(BR - R) + (BL - L)|}$$

Figure 8.

This modification is identical with 1_0 in the first quadrant. In the third quadrant, where both BR - R and BL - L are negative, the behavior of 1_1 is consistent with the assumption relating laterality and baseline shifts. However, in quadrants II and IV inconsistencies again arise. There exist points of equal BL - L, for example, which would be indexed by 1_1 in a manner contradicting the assumption that a greater decrease from baseline BR - R is associated with greater lateralization to the right hemisphere. In addition, 1_1 also suffers from the undesirable quality of taking on unbounded values for points near the line BR - R - -(BL - L).

Figure 9 presents the isolaterality contours of an index 1_2 which avoids these problems. This index is identical with 1_0 and 1_1 when both BR - R and BL - L are positive. It agrees with 1_1 in the third quadrant and so is consistent there. However, it assigns to any data point in the second quadrant the value -1.0 and to any point in quadrant IV the value 1.0. While l_2 is not inconsistent with the assumption relating laterality to baseline shifts, it fails to rank data points within the second or fourth quadrants; information is therefore lost in such situations.

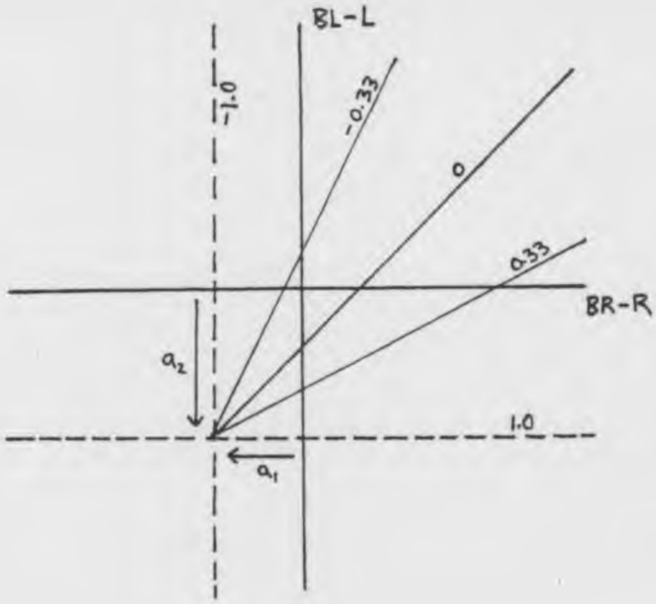


$$l_2 = \frac{(BR - R) - (BL - L)}{|(BR - R)| + |(BL - L)|}$$

Figure 9.

A third variant of l_0 is obtained by adding positive constants a_1 and a_2 to the baseline shifts so that the adjusted variables BR - R + a_1 and BL - L + a_2 never take on a negative value for all experimental data points to be ranked. Relevant isolaterality contours for this index, l_3, appear in Figure 10.

The addition of sufficiently large constants a_1 and a_2 has the effect of shifting the coordinate system in the direction of the third quadrant so that all experimental data points now fall into the region where both of the adjusted variables are positive. The index l_3 thus avoids all the problems associated with quadrants II, III, and IV in indices l_0, l_1, and l_2.



$$l_3 = \frac{(BR - R + a_1) - (BL - L + a_2)}{(BR - R + a_1) + (BL - L + a_2)}$$

Figure 10.

The laterality index l_3 is effectively a compromise between the indices $l_0 = \frac{(BR - R) - (BL - L)}{(BR - R) + (BL - L)}$ and $D = (BR - R) - (BL - L)$. As the values of the positive constants a_1 and a_2 are increased, the isolaterality contours of l_3 become increasingly parallel in the critical first quadrant and the quotient $l_3 = \frac{(BR - R + a_1) - (BL - L + a_2)}{(BR - R + a_1) + (BL - L + a_2)}$ approaches a scaled version of D.

The laterality index l_3 avoids the problems of the indices l_0, l_1, and l_2 and is consistent with the assumption that the right and left side alpha shifts from baseline BR - R and BL - L are accurate measures of hemispheric activation, with a greater baseline shift (greater alpha suppression) corresponding to greater hemispheric activation. It must be recognized, however, that this assumption does not specify l_3; the index l_3 (or, more correctly, class of indices of the l_3 type) is just one of an infinite set of indices consistent with the assumption. Even once the l_3 index type has been decided upon, the problem of the choice of the constants a_1 and a_2 remains. The value of these constants will determine how the index will rank the experimental data. In the absence of a more detailed knowledge of the relationship between hemispheric lateralization and the magnitude of baseline shifts, the selection of a_1 and a_2 is arbitrary.

The index-free ranking procedure given by:

(L_1, R_1, BL_1, BR_1) is greater right lateralized than (L_2, R_2, BL_2, BR_2)

if and only if $BL_1 - L_1 < BL_2 - L_2$ and $BR_1 - R_1 > BR_2 - R_2$

avoids the scaling problems of the above indices and has the advantage of not making additional and unjustifiable assumptions about the relationship between baseline shifts and laterality. It is the most parsimonious means of making comparisons of degree of lateralization under the second approach.

The <u>third approach</u> takes the right and left baseline shifts BR - R and BL - L, considered in relation to the corresponding initial right and left baseline levels BR and BL from which they arise, as the appropriate indicators of hemispheric activation. The underlying assumption in this approach is that a cerebral hemisphere with a comparatively high initial baseline level will exhibit a larger alpha suppression than a hemisphere of lower baseline activity in achieving the same level of cognitive activation. A plausible justification for this assumption is the concept that whatever factor might be acting to produce a right/left difference in <u>baseline activity</u> also would produce a similar difference in <u>shifts from baseline</u>. A greater skull thickness over one hemisphere would tend to reduce the baseline activity recorded from that hemisphere. But it would similarly reduce the measured shift from baseline induced during the experimental task, thus necessitating a comparison of the baseline shift to initial baseline for an accurate indication of cognitive activation.

A laterality index consistent with this third approach is

$$t = \frac{BR - R}{BR} - \frac{BL - L}{BL}$$

In this index, the baseline shift for each side is directly scaled by the baseline level for that side. It is important to distinguish this type of scaling from that described above for the index 1_0 and its variants. There, each baseline shift was scaled by the sum of the right and left baseline shifts; here, the baseline shift on each side is scaled by the initial baseline level on that same side -- a crucial difference.

Although the laterality measure t is a satisfactory index, it must be pointed out that the assumptions of the third approach do not uniquely determine it; two further assumptions are implicit in its use.

First, a specific way of scaling for the initial baseline activity has been assumed. Dividing each baseline shift by that sides' baseline level is but one of many ways to scale for initial activity. For example,

$$t_{a_0} = \frac{BR - R}{BR + a_0} - \frac{BL - L}{BL + a_0}$$

where a_0 is any positive constant, would be another acceptable measure. Here the value of a_0 determines the relative contribution of the scaling effect; as $a_0 \rightarrow \infty$, t_{a_0} effectively approaches the difference measure $D = (BR - R) - (BL - L)$.

Second, a specific relation between the magnitude of the scaled baseline shifts and the degree of lateralization has been assumed.

A means of making comparisons of degree of lateralization without making this second assumption is the index-free ranking procedure defined by:

(L_1, R_1, BL_1, BR_1) is greater right lateralized than (L_1, R_2, BL_2, BR_2)

if and only if $\frac{BL_1 - L_1}{BL_1} < \frac{BL_2 - L_2}{BL_2}$ and $\frac{BR_1 - R_1}{BR_1} > \frac{BR_2 - R_2}{BR_2}$

If, in addition it is desired not to invoke the first assumption, the following index-free ranking procedure can be employed:

(L_1, R_1, BL_1, BR_1) is greater right lateralized than (L_2, R_2, BL_2, BR_2)

if and only if

$BL_1 - L_1 < BL_2 - L_2$ and $BL_1 > BL_2$ and $BR_1 - R_1 > BR_2 - R_2$ and $BR_1 < BR_2$

This procedure, which makes no additional assumptions, is the most general means of making comparisons of degree of lateralization under the third approach in which right and left baseline shifts are compared while taking into account initial baseline levels.

This concludes the discussion of the underlying assumptions, candidate laterality indices, and appropriate index-free ranking procedures for the three approaches to interpreting EEG alpha asymmetries in making comparisons of degree of lateralization. These approaches and their corresponding index-free ranking procedures are summarized below. In each case the conditions for the ranking of (L_1, R_1, BL_1, BR_1) as greater right lateralized than (L_2, R_2, BL_2, BR_2) are given.

1) The levels of EEG alpha activity recorded from the right and left sides during the experimental task are accurate indicators of degree of lateralization, with a lower level of alpha activity corresponding to a greater degree of cognitive activation.

$$L_1 > L_2 \text{ and } R_1 < R_2$$

2) The value of the experimental task-induced shifts from initial baseline alpha activity on the right and left sides are accurate

indicators of degree of lateralization, with a greater decrease from baseline corresponding to higher cognitive activation.

$$BL_1 - L_1 < BL_2 - L_2 \text{ and } BR_1 - R_1 > BR_2 - R_2$$

3) The value of the task-induced baseline shifts, each considered in relation to the initial baseline level on the same side, are accurate indicators of degree of lateralization, with a greater decrease from baseline accompanying an initially lower baseline level corresponding to higher cognitive activation.

$$BL_1 - L_1 < BL_2 - L_2 \text{ and } BL_1 > BL_2 \text{ and } BR_1 - R_1 > BR_2 - R_2 \text{ and } BR_1 < BR_2$$

Finally it should be noted that if none of the assumptions behind the three approaches described above can be justified, then the only recourse that still allows comparisons of degree of lateralization would be to use the conjunctive index-free ranking procedure given by:

(L_1, R_1, BL_1, BR_1) is greater right lateralized than (L_2, R_2, BL_2, BR_2)

if and only if

$$L_1 > L_2 \text{ and } BL_1 - L_1 < BL_2 - L_2 \text{ and } BL_1 > BL_2 \text{ and}$$
$$R_1 < R_2 \text{ and } BR_1 - R_1 > BR_2 - R_2 \text{ and } BR_1 < BR_2$$

Any pair of experimental data points which satisfy these criteria necessarily are ranked identically by the three index-free ranking procedures listed above. This is the most assumption-free, conservative procedure for making comparisons of degree of hemispheric lateraliation based on EEG alpha asymmetries.

VII. CONCLUDING REMARKS

This paper has discussed methodological issues related to using numerical indices derived from the experimental data in making comparisons of degree of hemispheric lateralization. Different indices of lateralization represent theories specifying the relationship between the observed surface measures and the underlying neurophysiological asymmetry. In many studies the rationale for the index employed is not stated and the underlying assumptions cannot be justified. Index-free ranking procedures offer a method of making comparisons of degree of lateralization which require the fewest theoretical assumptions. The utility of these procedures is limited, however, due to the fact that they provide only an incomplete ordering, i.e., all of the experimental data points may not be comparable. The price paid for the procedures' economy of assumptions is a reduced practical usefulness.

The bottom line of this discussion is that prudence is required in hemispheric lateralization research. Investigators must recognize that conclusions about differences in the degree of lateralization arrived at through the use of numerical indices whose implicit assumptions are unjustified cannot be logically upheld. Index-free ranking procedures should be given due consideration, but when these are opted against for reasons of restricted applicability, the assumptions underlying the laterality index that is employed should be understood and explicitly stated.

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