Electroencephalography and clinical Neurophysiology, 1985, 62: 203–208
Elsevier Scientific Publishers Ireland, Ltd.

SCALP DISTRIBUTIONS OF EVENT-RELATED POTENTIALS: AN AMBIGUITY ASSOCIATED WITH ANALYSIS OF VARIANCE MODELS

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(Accepted for publication: December 18, 1984)

An important question in event-related potential (ERP) experiments is whether ERP scalp distributions differ between experimental conditions, subject groups, or components. Scalp distributions are an important criterion for identifying ERP components (for discussion, see Donchin et al. 1978; Picton and Stuss 1980; Sutton and Ruchkin 1984) because of the biophysical fact that different potential field distributions on the scalp indicate different spatial configurations of intracranial current sources (Vaughan 1982; Wood 1982; Wood et al. 1984). This interpretation assumes, of course, that distributional differences reflect differences in neural activity and are not due to differential eye movements, muscle activity, or other artifacts between conditions.

Differences between scalp distributions are often assessed in the same analysis of variance (ANOVA) used to assess the statistical significance of experimental manipulations. The simplest form of such an analysis is a 2-way Location × Condition design in which the Location main effect indicates whether there are differences between Locations averaged over all Conditions, the Condition main effect indicates whether there are differences between levels of the Condition factor averaged over all Locations, and the Location × Condition interaction indicates whether there are differences in the pattern of voltage across Locations in different Conditions. Based on conventional interpretations of ANOVA interactions (e.g., Winer 1962), significant Location × Condition interactions are typically interpreted as demonstrating different scalp distributions for different Conditions, hence implying different configurations of current sources. Although our results are presented in terms of Location × Condition designs, the same considerations apply to ANOVAs involving scalp distributions for different groups of subjects (i.e., Location × Group interactions) and for different ERP components (i.e., Location × Component interactions).

The use of interactions involving electrode location to assess differences between scalp distributions initially appears to be both conceptually and statistically sound: such differences must be due (apart from artifacts) to changes in source configuration, location, or extent, and the additive ANOVA model is one of the most robust, well-studied techniques in inferential statistics. However, there is a basic incompatibility between the additive ANOVA model and the multiplicative effect on ERPs produced by changes in source strength. That is, a 2-fold increase in source strength, for example, produces a corresponding 2-fold increase in the voltage at each location instead of adding a constant voltage to each location as assumed by the ANOVA model. Consequently, significant Location × Condition interactions can result solely from a change in source strength, indicating that shape differences between scalp distributions cannot be unambiguously derived from ANOVA interactions involving electrode location.

In this paper we use potential distributions generated by dipole sources in spherical volume conductor models: (a) to illustrate the incompatibility of the ANOVA model for ERP data; (b) to demonstrate that it is not merely a theoretical curiosity but occurs under conditions of noise

0168-5597/85/$03.30

approximating those of empirical ERP data; and (c) to demonstrate that the incompatibility can be circumvented by suitable scaling of the data before ANOVAs are computed. This problem has been addressed by Hansen and Hillyard (1980) but has not received adequate attention in the literature.

Methods

To illustrate the incompatibility of the additive ANOVA model with ERP data, we simulated Location × Condition 2-way ANOVAs with significant effects of Location and Condition, both with and without changes in source location (and hence with and without changes in distributional shape). In each analysis to be described, the Location factor had 3 levels and the Condition factor had 2 levels. Such a design would be appropriate, for example, for an experiment investigating 2 levels of stimulus intensity measured at each of 3 electrode locations.

The shapes of the basic scalp distributions, and hence the Location main effects, were determined by calculating the surface potential fields generated by dipole sources in a 4-sphere model of the head (cf., Cuffin and Cohen 1979; Darcey et al. 1980). The brain was represented by a 10 cm inner sphere, with outer shells of 10.2, 10.9 and 11.5 cm representing cerebrospinal fluid, skull and scalp. Resistivities of the brain and scalp were assumed to be equal, and those of the skull and cerebrospinal fluid to be 80 times higher and 3 times lower, respectively (Rush and Driscoll 1968).

Condition main effects were introduced by reducing the dipole moment (i.e., strength) parameter for one level of the Condition factor relative to the other by one-half. The data for each cell in the 2 × 3 design consisted of 100 values sampled randomly from normal distributions determined by the Location and Condition effects; specific values are given below. ANOVAs were computed using BMDP4V (Dixon 1981).

Results and Discussion

The first example was designed to approximate a radial source in superficial cortex and employed a radial dipole source located 0.3 cm below the surface of the inner sphere representing the brain. The distributions generated by such a source are shown in Fig. 1A. One hundred values were randomly selected from normal distributions with means of 1.72, 3.70 and 8.90 for one condition and 0.86, 1.85 and 4.45 for the other, corresponding to electrode locations at 10, 30 and 50° from a point directly over the source; standard deviations of 5 were used for all conditions and locations. The source configuration, and hence the shape of the potential distributions, was identical for both conditions.

The consequence of the reduction in dipole strength is indicated by the distributions for the two conditions shown in Fig. 1A. The key point is that the size of the strength effect is not constant across locations as required for a main effect in a standard ANOVA model but is different at different electrode locations. This is because differences in dipole strength have multiplicative instead of additive effects as noted above. Consequently, the ANOVA model confuses differences in the amplitude of scalp distributions (due to differences in source strength) with differences in their shape (due to differences in source configuration).

This ambiguity is evident in the ANOVA results for the data in Fig. 1A, which indicated significant Location and Condition main effects (F (2, 198) = 71.86, $P < 0.001$, and F (1, 99) = 29.08, $P < 0.001$, respectively), but also a highly significant Location × Condition interaction (F (2, 198) = 6.24, $P < 0.003$) despite identical distributional shapes. Within the additive assumptions of the ANOVA model, this significant Location × Condition interaction is appropriate for these data because it indicates Condition effects of different magnitudes at different locations. However, from the perspective of assessing differences in distributional shape, this example clearly illustrates the incompatibility of the ANOVA model with the multiplicative effects produced by differences in source strength.

Fig. 1B shows that this ambiguity applies to tangential as well as radial sources. The location of the source was identical to that in Fig. 1A, and electrode locations were directly over the source and 30° on either side. Again, the dipole strength in one condition was half that in the other; the

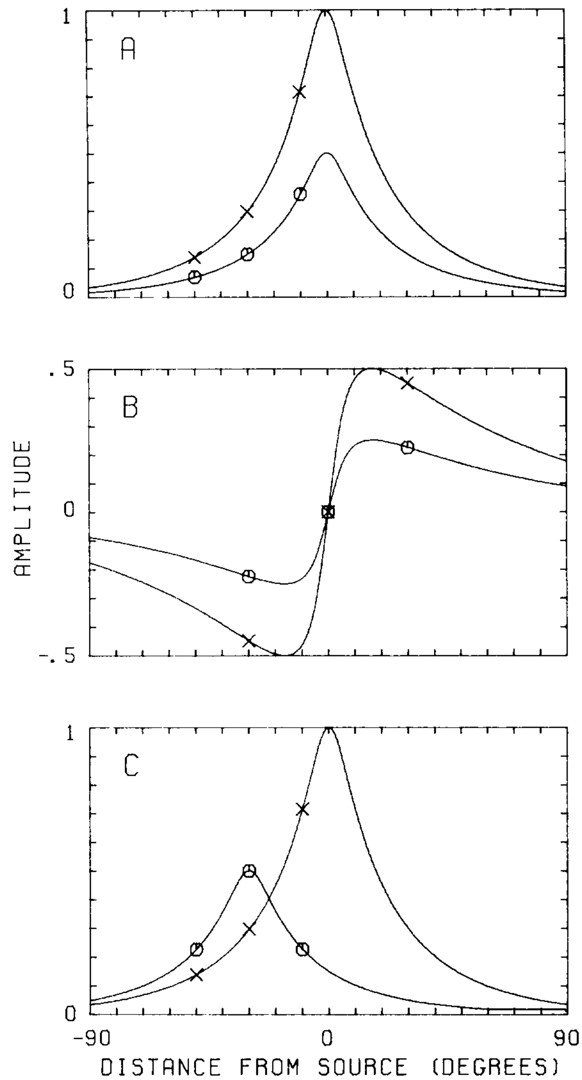

Fig. 1. A: potential distributions on the surface of a spherical volume conductor generated by a superficial radial dipole source. The two distributions were generated by sources that were identical in location and orientation, and differed only in strength. Source strength for the distribution denoted by O's was one-half that denoted by ×'s. Distributions are plotted on a scale determined by the range of the larger distribution. The plane of the figure passes directly through that of the dipole source. B: potential distributions under conditions identical to those in A except that the source was oriented tangentially instead of radially to the surface of the sphere. C: potential distributions under conditions identical to those in A except that the weaker source (denoted by O's) was located 15° away from that of the stronger source (denoted by ×'s).

mean voltage values from the dipole model were −3.98, 0.00, 3.98, and −1.99, 0.00, 1.99, respectively. The ANOVA for these data showed a significant main effect of Location (F (2, 198) = 80.19, $P < 0.001$) and a significant Location × Condition interaction (F (2, 198) = 8.70, $P < 0.001$). The Condition main effect was not significant in this example because the difference in dipole strength produced offsetting differences in positive and negative voltage on either side of the source. This example illustrates that even 'cross-over' interactions (Winer 1962, p. 244–247) do not necessarily indicate a difference in distributional shape. It also suggests that using Location × Condition interactions in absence of Location main effects as a criterion for genuine shape changes does not adequately protect against all cases of the ambiguity.

These results demonstrate that significant interactions of electrode location with experimental condition, group, or component cannot be interpreted as unambiguous demonstrations of shape differences between ERP scalp distributions and hence cannot be used to infer changes in source configuration. Although such interactions could be due to genuine shape differences, cases like those shown in Fig. 1A and B indicate that they can be produced by amplitude differences alone. Note that the likelihood of interactions due only to changes in source strength varies with the position of the recording electrodes relative to the distribution in question. For example, for the superficial dipole sources shown in Fig. 1A and B, interactions due to strength differences become less likely if the electrodes are located far lateral to the source (e.g., 80–90° in Fig. 1A and B). Here the amplitude effects are more nearly equal across locations as assumed by the ANOVA model. Similarly, surface distributions resulting from deeper or more extended sources are broader than those of superficial sources and, thus, produce less extreme violations of the additivity assumption.

The ambiguity posed by interactions involving electrode locations could be avoided if the source or sources of the surface potentials in question were known. In that case the data could be fit by an appropriate source model and the effects of experimental conditions could be assessed using

ANOVAs on parameters of the model instead of raw ERP voltages. Differences in voltage between electrode locations would then be explained automatically by the source model. Although in theory an ideal solution to the ambiguity, this strategy is unfortunately almost useless in the practical case because the sources of ERPs typically analyzed for interactions involving electrode location are rarely known. Indeed, it is precisely to help shed light on their sources that possible differences between scalp distributions are investigated.

An ad hoc but more practical approach to resolving the ambiguity is to scale the data before computing ANOVAs in order to eliminate amplitude differences between conditions, thereby focusing the analysis exclusively on differences in the shape or pattern of voltage differences across electrode locations. The question is how to choose the necessary scalar to achieve this purpose. One strategy is to normalize the data for the two conditions by finding the maximum and minimum values in each condition, subtracting the minimum from each data point, and dividing by the difference between maximum and minimum. It is essential to use the mean values at each electrode location instead of the raw data to determine the maximum and minimum in order to achieve a more stable estimate. To illustrate, when the data in Fig. 1A and B were normalized for each condition before computing the ANOVAs, the Location effect remained highly significant in both analyses (F (2, 198) = 56.8, $P < 0.001$, and F (2, 198) = 64.44, $P < 0.001$, respectively), whereas the Location × Condition interaction was not significant in either analysis (F (2, 198) = 1.18, $P > 0.31$, and F (2, 198) = 1.03, $P > 0.35$, respectively).

Fig. 1C demonstrates that scaling does not eliminate the ability to detect true changes in distributional shape due to source differences. This example is identical to that in Fig. 1A except that in addition to the difference in dipole strength, the location of the source in one condition differed from that in the other by 15°. In this case the Location × Condition interaction was significant both in the ANOVA on the raw voltages (F (2, 198) = 57.97, $P < 0.001$) and in the ANOVA in which the data were normalized in the manner described above (F (2, 198) = 35.68, $P < 0.001$).

A more general formulation of the scaling problem can be achieved by representing the ERP data as points in multidimensional space (see Protter and Morrey 1964, Ch. 1 and 7; Bock 1975, Ch. 2; Glaser and Ruchkin 1975, Ch. 5). In such a representation, the distribution for each condition is represented as a vector in N-space, the axes of which are the voltages at each of the N electrode locations. Represented in this manner, the amplitude of a given distribution is given by the length (norm) of its vector, whereas its shape is given by the vector's orientation. Vector length is defined by the square root of the sum of squared voltages over all electrode locations, and amplitude differences between conditions can be eliminated by scaling the voltages in each distribution by its corresponding vector length. For the data shown in Fig. 1, scaling by vector length produces equivalent results to the normalization described above; that is, it eliminated the Location × Condition interactions in Fig. 1A and B but not in C. Although normalization and scaling by vector length would probably yield similar results in many situations, the latter has a more sound theoretical basis and is less susceptible to noise because it is based on the values at all electrode locations instead of only the maximum and minimum. As noted for the normalization procedure above, it is important to calculate vector lengths using mean values instead of the raw data in order to minimize the effect of noise on the estimates.

A third procedure, similar in some respects to both of the above, was used by Hansen and Hillyard (1980). They chose a scalar that resulted in the mean values across electrode locations within each condition equaling a specified value, in their case -1 μV. For radial sources, this procedure eliminates interactions due solely to amplitude effects in a manner similar to normalization and vector length scaling. However, it does not adequately correct the shape-amplitude ambiguity for tangential sources since the means across locations are equal in the two conditions. Note that this 'cross-over' pattern can occur not only around zero as in the pure tangential case shown in Fig. 1B, but around any positive or negative mean value if tangential and radial sources are simultaneously active.

An undesirable byproduct of the scaling procedures is that they eliminate Condition main effects (if present). Except for performing ANOVAs on parameters of appropriate models of known sources as described above, we know of no way to assess both overall amplitude effects (i.e., Condition main effects) and differences in distributional shape (i.e., Location × Condition interactions) in a single analysis while simultaneously avoiding the ambiguity between multiplicative effects and the ANOVA model. If it is necessary in a particular experiment to assess both overall amplitude effects and distributional differences, then a conventional ANOVA to assess Condition main effects could be followed by a second ANOVA on the scaled data to assess possible shape differences. Alternatively, one could use the multidimensional space representation described above to express amplitude as vector length and distribution shape as a set of direction cosines (e.g., Bock 1975, Ch. 2) and perform separate ANOVAs directly on these quantities.

We re-emphasize that ANOVA interactions due to differences in amplitude instead of distributional shape may or may not be present in any given set of empirical ERP data, but there is no way to tell unless the source or sources of the potentials in question are known. Although we have discussed this ambiguity in terms of distributions generated by single dipole models, the same considerations apply to distributions generated by any configuration of sources. Further, they apply not only to base-to-peak and peak-to-peak ERP amplitude measures, but also to area measures, scores derived from principal component analysis, or to any other technique in which amplitude differences between electrode locations are not explained by appropriate volume conduction models of known sources. Finally, the incompatibility between ERP data and the additive ANOVA model applies not only to scalp distributions but to any experimental design in which the pattern or shape of ERP voltage across treatment levels is investigated.

Summary

Analysis of variance (ANOVA) interactions involving electrode location are often used to assess the statistical significance of differences between event-related potential (ERP) scalp distributions for different experimental conditions, subject groups, or ERP components. However, there is a fundamental incompatibility between the additive model upon which ANOVAs are based and the multiplicative effect on ERP voltages produced by differences in source strength. Using potential distributions generated by dipole sources in spherical volume conductor models, we demonstrate that highly significant interactions involving electrode location can be obtained between scalp distributions with identical shapes generated by the same source. Therefore, such interactions cannot be used as unambiguous indications of shape differences between distributions and hence of differences in source configuration. This ambiguity can be circumvented by scaling the data to eliminate overall amplitude differences between experimental conditions before an ANOVA is performed. Such analyses retain sensitivity to genuine differences in distributional shape, but do not confuse amplitude and shape differences.

Résumé

Potentiels liés à l'évènement: distribution de scalp

Les analyses des interactions de variances (ANOVA) prenant en compte la localisation de l'électrode sont souvent utilisées pour déterminer la significativité statistique des différences entre les distributions de scalp des potentiels liés à l'événement (ERP) pour diverses conditions expérimentales, divers groupes de sujets ou diverses composantes du potentiel évoqué. Toutefois, il existe une incompatibilité fondamentale entre le modèle additif sur lequel sont basées les ANOVA et l'effet multiplicatif produit par des différences de puissance de la source sur les amplitudes des ERP. En utilisant les distributions de potentiels engendrées par des dipoles dans un volume conducteur sphérique, nous avons démontré que des interac-

tions très significatives considérant la localisation de l'électrode, peuvent être obtenues entre des distributions de scalp de formes identiques produites par la même source. De telles interactions ne peuvent donc pas être utilisées comme indications non ambiguës de différences de formes entre distributions ou même de différences de configurations des sources. Cette ambiguité peut être palliée en échelonnant les données de façon à éliminer l'ensemble des différences d'amplitude entre les diverses conditions expérimentales, avant d'effectuer une ANOVA. De telles analyses conservent leur sensibilité aux vraies différences de forme de distributions, mais ne confondent plus différences de forme et d'amplitude.

Supported by the Veterans Administration and NIMH Grant MH-05286.

We thank Drs. T. Allison, T.M. Darcey and D.S. Ruchkin for comments on the manuscript and for helpful discussion of the scaling problem. Dr. Ruchkin suggested the vector formulation of the scaling problem.

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