LOCALIZATION OF AUDITORY EVOKED POTENTIALS RELATED TO SELECTIVE INTERMODAL ATTENTION

Joseph Dien[1, 3], Don M. Tucker[1, 2], Geoff Potts[1, 4, 5], and Ann Hartry-Speiser[1, 2]

[1]Institute of Cognitive and Decision Sciences, Department of Psychology, U. of Oregon

[2]Electrical Geodesics, Inc.

[3]Cognitive Psychophysiology Lab, Department of Psychology
University of Illinois at Urbana-Champaign

[4]Dept. of Psychiatry, Harvard Medical School

[5]Neuroimaging Laboratory, Brockton Veterans Administration Medical Center

Dien, J., Tucker, D. M., Potts, G., and Hartry-Speiser, A. (1997). Localization of auditory evoked potentials related to selective intermodal attention. Journal of Cognitive Neuroscience, 9(6)799-823.

https://www.mitpressjournals.org/doi/abs/10.1162/jocn.1997.9.6.799

This research was supported by NIMH grants MH42129, MH42669, MH18935, and MH19554, by a grant from the Pew Memorial Trusts and the James S. McDonnell Foundation to support the Center for the Cognitive Neuroscience of Attention, and by Small Business Innovation Research grant MH51069 to Electrical Geodesics Incorporated, Eugene, OR.

Portions of these findings were presented at the meeting of the Pacific division of the American Association for the Advancement of Science, San Francisco, June, 1994 and the meeting of the Cognitive Neuroscience Society, San Francisco, April, 1996. Thanks to Mike Posner, Greg Miller, Gordon Logan, and two anonymous reviewers for their helpful comments on earlier drafts.

Running Head: *Source of Nd*

Abstract

A long-standing question in attention research is to what extent selection involves gates in the sensory stream and to what extent they involve added secondary processes. Intermodal attention paradigms are useful for examining this issue since different modalities involve readily distinguished cortical regions. Evoked potential studies have identified an attention related frontal negativity labeled the Nd in auditory attention studies. It has been suggested that it arises from modulation of auditory cortex (compatible with gating mechanisms) or of frontal cortex (compatible with secondary processes such as short-term memory buffers). Efforts to localize the Nd have been impaired by the finding that the Nd comprises multiple components. Some novel procedures utilizing principal components analysis, in conjunction with high-density 64-channel recordings, were used to address this issue. Results suggest that the major source of the early Nd (the portion of most interest) resides in the frontal cortex, supporting the secondary process view for this particular mechanism.

Descriptors: event-related potential, Nd, topography, factor analysis, attention, auditory.

Localization of Auditory Attention Evoked Potentials

Joseph Dien, Don M. Tucker, Geoff Potts, and Ann Hartry

A long-standing question in attention research is to what extent selection involves gates in the sensory stream and to what extent they involve added secondary processes. In the cognitive literature, the two extreme positions is that selection occurs when early filters restrict the information passed on for further processing (Broadbent, 1958) and that selection occurs well after sensory processing has been completed (Deutsch & Deutsch, 1963). A parallel debate has taken place in the cognitive neuroscience literature with one position being that selection is an emergent property of limitations in the sensory cortex (Allport, 1993) and the other position being that selection involves general purpose executive functions located outside of sensory cortex (Posner & Petersen, 1990).

Intermodal attention paradigms are useful for examining this issue since different modalities involve readily distinguished cortical regions. A regional cerebral blood flow study (rCBF) study of intermodal attention found evidence for attention related activity changes in a wide array of regions (Roland, 1982). Subjects were presented with stimuli in the auditory, somatosensory, and visual modalities simultaneously and asked to make discriminations within one of them. As might be expected, attention to a given modality increased activity in the associated sensory cortex. As compared to when only a single modality was presented, attentional selection in the trimodal situation also activated superior medial cortex. Unfortunately, the xenon injection method used is not able to measure cingulate activity, an area implicated in attentional processes (Posner & Petersen, 1990). Some regions outside of sensory cortex also displayed modality-specific modulation. For example, the right prefrontal cortex (roughly area 46) was modulated by auditory attention alone. Unfortunately, rCBF studies provide virtually no information about the time course of these regions (Roland, 1993).

Intermodal Attention-Related Evoked Potentials

Event-related potentials (ERPs), on the other hand, have the temporal resolution to examine this issue although they have low spatial resolution. ERP studies of auditory attention have identified a frontal negativity, the Nd, that is tentatively divided into two components, the Nde (early Nd) and the Ndl (late Nd) (Woods, 1990). The Nd is enhanced to stimuli occuring on an attended channel as defined by such features as ear of presentation, sensory modality, or pitch (Näätänen, 1992). The Nde is an early negativity with an onset latency of about 60 ms. It lasts until the P200 and has a frontal distribution centered on Fz (Woods, 1990), although the latency is longer for larger intertrial intervals (Hansen & Hillyard, 1984). The Ndl is a slower overlapping negativity that peaks about 350 ms after stimulus delivery and lasts till some 500 ms or so. It has a more frontal distribution centered on Fpz (Hansen & Hillyard, 1980). In addition, an intervening positivity, Pd, has been described that is enhanced to attended stimuli, particularly in intermodal attention paradigms (Alho, Woods, Algazi & Näätänen, 1992; Hackley, Woldorff & Hillyard, 1990; Woods, Alho & Algazi, 1992). Some evidence suggests that there may also be a lateral Nd reflecting modulation of lateral temporal lobe activity (Alho et al., 1992; Hackley et al., 1990). In other research the Nde has been suggested itself to have two portions, peaking at 80 and 125 ms (Giard, Perrin, Pernier & Peronnet, 1988; Woldorff & Hillyard, 1991).

Unfortunately, it has been difficult to characterize the Nd attention effect since this feature is not measured directly but is computed as a difference wave. As can be seen in the listing of Nd effects, there is some question about how many constituents there are. Moreover, the temporal and spatial overlap makes it difficult to determine when the Nde ends or the Ndl begins. It is not even certain that the Nde and the Ndl are separate features. Their chief point of differentiation, topography, could be affected by the overlap of other components that are also sensitive to attention.

Researchers have concentrated on characterizing the Nde as its early latency makes it the most likely to have a role in selection. There are two chief cognitive theories of the Nde. One hypothesis is that the Nde is due to attentional amplification of the auditory N1 event, much as modulation of exogenous components have been observed in the visual evoked potential (Hillyard, Hink, Schwent & Picton, 1973; Woldorff & Hillyard, 1991). This interpretation is clearly compatible with the construct of early gating. The other hypothesis is that it reflects an attentional trace maintained in a type of echoic memory, indexed by a processing negativity (PN) that overlaps but is separate from the classic N1 (Näätänen, 1990; Näätänen, Gaillard & Mäntysalo, 1978; Teder, Alho, Reinikainen & Näätänen, 1993). Such a process could occur either as part of sensory processing or by a separate secondary mechanism. Recent findings suggest that there are both PN and N1 contributions to the Nd (Woods, Alho & Algazi, 1994).

The localization and nature of the PN remains controversial. One position is that it arises from the auditory cortex (Näätänen, 1985) while another position is that it arises in amodal frontal cortex, probably the medial surface (Woods, 1990). The former would be supportive of a process conducted in the course of sensory analysis whereas the latter is more indicative of a secondary process. Thus, localization in conjunction with neuroanatomical information could clarify the nature of this attention-related process. Moreover, if the PN did in fact emanate from frontal cortex, then neuropsychological knowledge about the locus could be used to evaluate the comparison account.

Localization of Event-Related Potentials

While localization of ERP components is difficult (c.f., the inverse problem; Nunez, 1981), the use of high-density electrode montages and biophysical principles makes it possible to approximate source locations. Event-related potentials are the electrical fields produced as the brain responds to an event. While all neural activity will produce potential fields, only synchronous activity of similarly aligned neurons will produce fields recordable at the scalp. These fields will necessarily be dipoles with both a negative and a positive pole (Nunez, 1990). Thus, a given electrical event will produce positive fields in one direction and negative fields in the other. All things being equal, the field will be most focal along the axis of the dipole, especially on the side closest to the scalp. In the ideal case, this makes it relatively simple to determine the source of an electrical event. One merely determines the orientation of the dipole and the relative intensity of the two foci on the scalp (Scherg, 1990).

Unfortunately, the situation is complicated by the superposition problem (Nunez, 1981). At any time, multiple neural sources are active. Moreover, volume conduction ensures that each source contributes to the potential field at every point on the surface. A given recorded potential represents the sum of an undetermined number of sources with unique but unknown spatial and temporal characteristics. Such overlapping events can introduce significant errors in localization procedures (Zhang & Jewett, 1993). Localization routines are also compromised when the number of dipoles is unknown (Achim, Richer & Saint-Hilaire, 1991), which is normally the case.

Application of Principal Components Analysis

One way of addressing these issues is to use principal components analysis (PCA) (Gorsuch, 1983). PCA is a method for identifying the pattern of covariance in a set of measurements, such as that produced by an ERP component (Donchin & Heffley, 1979). It can therefore be used to separate superimposed features by identifying different patterns of covarying time points, even if they overlap.

PCA separates statistically unique patterns in time using algorithms that do not dictate any manner of spatial patterning. An initial question is whether the principal components are spatially coherent, due to the structure of the dataset, as would be consistent with physical sources. Dien and Tucker (in submission) applied PCA to a 64-channel visual ERP in a word-reading experiment and found principal components that were dipolar (e.g., with positive and negative field potentials in opposite directions). Most of these components replicated in an independent sample of subjects. It could therefore help disambiguate the different features and improve dipole modeling efforts.

The typical PCA analysis (temporal PCA) uses the waveforms as the observations and the voltage samples as the variables. Each waveform represents a particular channel from a particular subject from a particular condition. The practice of including multiple observations from a single subject (different sites and conditions) sometimes elicits objections; this objection is based on a misguided analogy to inferential statistical tests. PCA is a descriptive technique and so no significance testing is done. Instead, this practice may be better thought of as increasing the signal to noise ratio by adding site and condition covariance. Likewise, autocorrelation is not a problem as it is for regression since there are no significance tests to be inflated by correlated error variance.

The PCA method has important limitations. One is that the waveforms are defined in terms of fixed time points and therefore cannot account for latency changes within the observation set. Latency shifts across subjects or conditions may result in an extra component that resembles the time-derivative of the underlying component (Möcks & Verleger, 1986). Such cases can be detected with high-resolution topographical information since latency jitter factors should have the same topography.

A more serious problem is misallocation of variance (Wood & McCarthy, 1984). Two ERP components with the same time course will be fit by the same factor waveform even if the ERP components represent spatially distinct sources; partial temporal overlap can result in partial misfitting. Finally, some misallocation of variance may occur to the extent that the rotation procedure does not adequately differentiate the separate components. This problem can also be alleviated with a high-density montage as misallocated effects should have the topography of the original factor rather than that of the second factor (Chapman & McCrary, 1995).

These difficulties have restricted the use of PCA as an analysis tool for ERP studies. However, as Wood and McCarthy emphasized, the more traditional windowed analyses also suffer from the ambiguity of superposition.

> "We have thus far considered the problem of misallocation of variance exclusively from the perspective of PCA [principal components analysis]. . . Other approaches to ERP [event-related potentials] analysis, measurement of peak amplitudes and latencies for example, are no less subject to the problem of component overlap than PCA; they simply make it easier to ignore by not representing it explicitly. Misallocation of

> variance and misinterpretation of experimental effects are just as possible using such techniques as they are with PCA," (Wood & McCarthy, 1984) p. 258.

Thus, PCA does not so much introduce a problem into the analysis as it provides additional information for helping resolve an existing problem. Latency jitters already creates interpretational problems, such as whether the N400 is a delayed N2b (Deacon, Breton, Ritter & Vaughan, 1991; Polich, 1985). Likewise, a condition effect in the P2 window could actually be due to an overlapping P3; in this case, a P3 condition effect might be "misallocated" to the P2. PCA helps identify such problems which may otherwise be missed. Although one might wish that one could dispense with the additional work of conducting PCA, it is an often necessary tool for performing good science.

Utilizing PCA as a step preceding dipole localization has a couple benefits. Unlike the PCA functions included in commercial packages like BESA, such an analysis can take advantage of individual difference and condition variance as it is not limited to a single set of waveforms. Secondly, although PCA does not eliminate the distortions produced when modeling simultaneous dipoles (Zhang & Jewett, 1993), it does facilitate the evaluation and detection of such distortions by separating variance allocation into a distinct step that can be independently examined and does so without making invisible assumptions that are still in the process of being validated, as opposed to alternative methods like MUSIC (Mosher, 1992).

In the present research, we apply PCA to an intermodal attention dataset to help resolve these dimensionality and overlap problems. To the extent that components have unique scalp topographies, it is expected that increased spatial resolution will facilitate the PCA process. We reasoned that if the PCA factors prove to be plausible approximations to ERP components, and they are spatially coherent in their scalp field distributions, then dipole modeling may yield useful information on the neuroanatomical sources of psychologically sensitive components.

To examine intermodal auditory attention, subjects were asked to attend to either auditory or visual modalities to detect targets in a simple 50/50 oddball paradigm with stimulus modality varied randomly each trial. Stimuli were randomly presented to either the left or right field. Since sensory information tends to be processed most in the hemisphere contralateral to the stimulus, this manipulation could assist localization of ERP sources. The visual evoked potential data was examined only to determine if any of the auditory attention effects were cross-modal.

Results

Since the auditory condition is of primary interest, it was analyzed first. An initial PCA was run to gain information about the underlying dimensionality of the dataset. Guided by these results, a windowed analysis of variance was conducted to characterize the traditional peak and trough components in the dataset. The PCA factor scores were then analyzed and compared to the windowed analyses.

Peak Analysis

In order to evaluate the PCA results, components were visually identified in the grand average data. For each component, a focal recording site was identified from the literature and the peak latency at that site was measured. See Figures 1-3 for the grand average waveforms. Figure 4 presents an averaged-mastoid reference version of Figure 2 for comparison sake.

According to a recent review (Näätänen, 1992), the late vertex exogenous auditory components are the P1 (50 ms), the N1 (100 ms), and the P2 (180-200 ms). Corresponding peaks were identified at Cz at latencies of 36, 104, and 208 ms respectively. In addition, a lateral N1 component (labelled variously Tb, N140, or N1c) has been reported at T4 at about 150 ms (Wolpaw & Penry, 1975). Indeed, a distinct negative peak is clearly visible at 160 ms in channel 54, near T4.

The distortion of the scalp topography caused by treating the reference site as inactive can be seen in these figures. The N1, for example, appears solely as a vertex-negative wave in the mastoid-referenced plot. In the average-referenced plot, this component is negative-going dorsally, but positive-going ventrally, with a definite inversion over the superior temporal plane.

Insert Figures 1-4 about here

The chief endogenous components are the P300 and the Slow Wave (Squires, Squires & Hillyard, 1975) which are enhanced to targets. These two components have variable latencies depending on task demands, with the Slow Wave coming second. They may best be distinguished by scalp topographies with the P300 being parietal-central maximal and the Slow Wave being parietal positive and frontal negative (Sutton & Ruchkin, 1984). When the attended target and standard conditions are compared, two positive peaks are indeed visible at posterior superior sites (e.g., at Cz at 372 ms and 528 ms). Corresponding negative peaks can be seen anteriorly, with an inferior frontal negative peak corresponding to the P3 and a more broadly distributed medial frontal negativity appearing to correspond with the Slow Wave (visible as a latency shift in the negative peak of the target effect in Figure 1 at sites 64 and 6).

When the attended and unattended standards are compared, a peak is seen at channel 3 just above Fz at 156 ms (Nde) and at channel 6 at 336 ms (Ndl) as well as a later prolonged negativity at both locations (Figures 5 & 6).

Insert Figures 5-6 about here

Factor Analysis

The initial factor analysis was conducted on the auditory stimulus trials alone. Inclusion of the visual stimulus trials would produce distortions because the PCA algorithm would attempt to fit factors to both types of evoked potentials even though many features are modality specific and are present in only one type of trial.

Principal components analysis (PCA) was used rather than principal axis factoring (PAF) since the two are essentially equivalent for datasets with many highly correlated variables (Gorsuch, 1983). Variables were centered on zero to eliminate effects of mean differences, but variances were not normalized; this statement is equivalent to declaring that a covariance matrix was used (which weights the time points by their variance) rather than a correlation matrix (which normalizes the variances) since covariance matrices tend to produce more plausible results (Curry et al., 1983). Cattell's Scree Test (Cattell, 1966; Cattell & Jaspers, 1967) indicated that nine factors should be retained, accounting for 87% of the variance. The retained factors were rotated using the promax procedure to improve interpretability and to relax the assumption of orthogonality. The waveform shape of the ninth factor lacked temporal coherence and was therefore dropped from further analyses.

Windowed ANOVAs

These PCA results were used to define the windows for the ANOVA analyses. In essence, the PCA factors indicate which time points covary, presumably due to the influence of a common electrical event. A time window is defined for each factor where it is most dominant in terms of factor loading magnitudes. The boundaries are set at the points where a factor first passes the falling curve of the prior factor. In some cases, the entire section overlaps with another factor (e.g., Factor 1 with Factors 7 & 8) in which case this other factor is ignored for the purposes of the time window (Figure 7). This procedure provides an objective criteria for setting the bounds for windowed analyses and for determining how many windows to set. Such criteria are particularly useful in a high-density dataset where different sites show different features and thus suggest different windows. As the selected channels and the following analyses will make clear, the resulting windows appear to bracket different components quite successfully. This procedure will also increase comparability between ANOVAs on the averaged data and ANOVAs on the factors.

Insert Figure 7 about here

Univariate repeated measures ANOVAs were conducted on the mean voltage of each window. For a crude spatial categorization, the sensors were grouped into twelve regional means (see Table 1) (Curran, Tucker, Kutas & Posner, 1993). These twelve regions were organized into two spatial ANOVA factors: hemisphere (left vs. right) and site (six regions: anterior ventral, anterior lateral, anterior dorsal, posterior ventral, posterior lateral, posterior dorsal). In addition, there were three experimental ANOVA factors of Field of presentation (left vs. right), Stimulus (target vs. standard), and Attend (listen vs. look). Greenhouse-Geisser epsilons (Geisser & Greenhouse, 1958) were used to correct for departures from sphericity. The set-wise Type I error rate was reduced below 1.0 by reducing the significance criteria to .03 (with five ANOVA factors, 31 tests * .03 = .93 errors per analysis set). Contrasts for interactions including Site were mostly computed for the region of most interest. Windows were named according to the major component expected to peak in that period. Since interest is solely directed at the attention manipulation, usually only effects involving it will be reported.

Insert Table 1 about here

The P50 window (4-64 ms) was examined for the 20-50 attention effect (Woldorff & Hillyard, 1991) but nothing is seen. The only significant effect is a hemispheric difference; even the site factor does not register significant differences between recording locations.

The N1 window (68-144 ms) was examined for an N1 attention effect but none is seen. The potential field is described as having an anterior dorsal negative peak and a posterior ventral positive.

The Nde/Tb window (148-180 ms) shows the expected attention effect. The scalp topography has an anterior lateral negative peak and a posterior ventral positive peak. Attention generally intensifies the anterior negativity: attend * stimulus * field * hemisphere * site, F(5, 75) = 4.457, p = .0089, e = .577. The only two exceptions are ipsilateral to left field standards and contralateral to right field targets. These exceptions may be due to the lesser intensity of the left hemisphere negativity that could reduce the chance of effects reaching significance.

The P2 window (184-288 ms) has an unexpected attention effect. The scalp topography has a positive dorsal (slightly more posterior) and a negative anterior ventral peak. There is a complicated effect which for the posterior dorsal region is characterized by a consistent enhancement by attention: attend * stimulus * field * hemisphere * site, F(5, 75) = 4.898, p = .0065, e = .550. Since the P2 has not generally been reported to be sensitive to attention, it is unclear whether the effect is due to it or to an overlapping feature; hopefully PCA will help clarify this issue.

The Ndl window (292-318 ms), as expected, shows a strong target effect. The scalp topography appears to reflect a vertical dipole tilted backwards, with negative anterior ventral and positive posterior dorsal peaks. There was a target effect mostly for attended stimuli that showed some laterality effects: attend * stimulus * hemisphere * site, F(5, 75) = 3.830, p = .0138, e = .639. For example, the target effect was more pronounced over the right anterior dorsal region (F[1, 75] = 26.805, p = .0001) than the left (F[1, 75] = 4.912, p = .0457). Also, targets produced more negative fields over the left anterior lateral region (F[1, 75] = 19.703, p = .0004) but not the right. No clear pattern is discernible in these effects.

In the P300 window (324-380 ms) also shows attentional and target effects as expected. The scalp topography has negative anterior ventral, positive posterior dorsal peaks. Attended targets in particular produced a general amplification across sites (especially at the posterior dorsal peak, F[1, 75] = 210.864, p = .0001) while unattended targets did not: attend * stimulus * site, F(5, 75) = 14.171, p = .0001, e = .386.

The Slow Wave window (384-648 ms) shows the usual target effects. The scalp topography has negative anterior lateral and posterior dorsal peaks. Amplitudes are larger when the auditory stimuli were attended: attend * site, F(5, 75) = 25.363, p = .0001, e = .439. Attended targets also enhance amplitudes, amplifying the anterior ventral and lateral negativity and the posterior dorsal and lateral positivity: attend * stimulus * site, F[5, 75] = 10.819, p = .0002, e = .428. Thus, overall the Slow Wave responds to the significant stimuli (attended stimuli, particularly when targets).

Interestingly, in the O-wave window (652-832 ms) an attention effect but no target effect is found. The scalp topography shows a negative anterior lateral, positive posterior dorsal peaks. Attention to the auditory stimuli enhances the O-wave (attend * site, F[5, 75] = 6.563, p = .0058, e = .363), causing the anterior dorsal region to become negative: F(1, 75) = 17.168, p = .0046.

Factor Score ANOVAs

The next step is to examine the PCA results themselves. Factor scores provide the amplitude of the latent waveforms in each recorded waveform. If the factor scores at each site are multiplied by the factor loading waveform (for oblique rotations, the factor pattern matrix) and then each time point is multiplied by its standard deviation, the result is the portion of the waveform accounted for by the factor (Figure 8). A proof is available from the authors. These waveform reconstructions can be plotted to examine the topography (Figure 9).

Insert Figures 8-9 about here

In addition, the factor scores can be treated in the same manner as the windowed means generated earlier. The results will be compared with the corresponding windowed analysis to determine how well the PCA factors capture the features of the conventional analysis. Disagreement will be evaluated as to whether they represent failures of these statistically derived latent waveforms to reflect the original components, or whether they represent disentangling of superposition ambiguities confounded by the windowed analyses. These factors will be examined in order of their peak times.

Factor 5 (P50 window) peaks at 52 ms and reflects a faint vertex positive peak with contrasting ventral negativities. Surprisingly, a target effect is present (attend * stimulus * field, F[1, 15] = 6.961, p = .0186) because attended right field targets produce a greatly reduced positivity: F(1, 15) = 23.080, p = .0002.

In some ways, this factor appears to be an improvement on the windowed analysis. It produced a topography which is compatible with that of the P50 (Wood & Wolpaw, 1982) and has statistically significant topographic peaks, whereas the windowed analysis did not. It lacks the hemispheric asymmetry of the windowed analysis which is reasonable since there is no reason to think the P50 should in fact be asymmetric in this experiment. On the other hand, it indicates a target effect that seems implausible at this early latency, although attention effects have certainly been found in this period (Woldorff & Hillyard, 1991). Replication is required.

Factor 4 (N1 window) peaks at 108 ms and reflects a frontal vertex negative peak and diffuse posterior positivity. No experimental effects reached the criteria level for significance, although there was a marginally significant tendency for right field stimuli to produce a contralateral enhancement: field * hemisphere * site, F(5, 75) = 3.281, p = .0323, e = .565.

This factor clearly corresponds to the N1, having the proper topography and time course (Näätänen & Picton, 1987). The waveform has a biphasic pattern, incorporating part of the succeeding P2 peak. Although the trend for a right field effect is interesting there is no reason to think that the right field should have any special effect on the N1. It has been reported that the N1 shows some contralateral enhancement (Näätänen & Picton, 1987). In any case, the topography of this effect shows that it is not due to an overlapping Tb.

Factor 8 (Nde/Ndl windows) peaks at 144 and 308 ms and reflects a focal negative peak on the frontal midline and a less distinct positive peak on the posterior midline. Attention increases the amplitude of this factor (attend * site, F[5, 75] = 7.466, p = .0065, e = .291) at the peak sites: anterior lateral (F[1, 75] = 9.176, p = .0034), anterior dorsal (F[1, 75] = 7.422, p = .0370), posterior ventral (F[1, 75] = 15.425, p = .0092).

The time course and topography of this factor is compatible with the Nde/Pd/Ndl complex (Figure 10). However, it only partly accounts for the Nde. Also, the second negative peak has about the correct latency for the Ndl, but it seems insufficiently frontal (Figure 11). As has been reported previously, this component(s) is enhanced by attention to a channel or modality (Woods, 1990). Unlike the corresponding interval of the windowed analyses, this factor is not responsive to field of presentation or stimulus type, suggesting that this factor has been successfully disentangled from the overlapping late positive complex.

Insert Figures 10-11 about here

Factor 6 (Nde/Tb window) peaks at 160 ms with a negative focus on the two frontal lateral surfaces and a single more diffuse positive peak in the posterior. There is a complicated interaction in which generally the factor is enhanced to attended stimuli: attend * stimulus * field * hemisphere * site, F(5, 75) =

5.517, p = .0044, e = .516. At the frontal negative foci, attention produces a more intense negativity to standards except ipsilateral to left field stimuli (left field, right hemisphere, F[1, 75] = 29.277, p = .0001; right field, left hemisphere, F[1, 75] = 19.255, p = .0011; right field, right hemisphere, F[1, 75] = 10.920, p = .0087). For targets there is an attention effect only ipsilateral to the stimuli (left ipsilateral, F[1, 75]= 7.238, p = .0249; right ipsilateral, F[1, 75] = 37.552, p = .0001). It is noticeable that the attention effect tends to be greater for the standards.

This factor has the scalp topography and time course of the Tb component of the T-complex (Wolpaw & Penry, 1975). As seen before (Woods et al., 1992), this factor was responsive to attention. Also, as seen previously, it appears to be larger over the right hemisphere (Woldorff & Hillyard, 1991; Wolpaw & Penry, 1975). Given the mixed results with the standards and targets, it is unclear whether this overall effect should be considered an attentional effect or a target effect.

Factor 3 (P2 window) peaks at 232 ms and has a positive vertex focus with a contrasting negativity along the inferior surfaces, particularly in the frontal region. There is a complex interaction which for the posterior dorsal positivity mostly reflects increases for attended stimuli: attend * stimulus * field * hemisphere * site, F(5, 75) = 3.538, p = .0239, e = .573. For standards, left field stimuli only show the attention effect, for both the left hemisphere (F[1, 75] = 11.035, p = .0068) and the right hemisphere (F[1, 75] = 26.208, p = .0001). For targets, except ipsilateral to left field stimuli, an attention effect is also seen: left field, right hemisphere (F[1, 75] = 51.956, p = .0001), right field, left hemisphere (F[1, 75] = 13.519, p = .0034), right field, right hemisphere (F[1, 75] = 9.321, p = .0114).

The topography and time course of this factor matches the P2 component (Näätänen, 1992). The waveform incorporates an N1 negativity which could indicate a biphasic pattern or could reflect correlation between the N1 and the P2. Examination of the topography of the attention effect suggests that it is due to an overlapping P300 (referring to the topography of the P300 factor) since it is not isomorphic with the topography of the factor. While the vertex maximum P2 covers both the anterior and posterior dorsal regions, the attention effect is virtually absent in the anterior (except ipsilateral to left field targets for some reason, F[1, 75] = 22.186, p = .0004). It is thus likely that this factor has misallocated some overlapping variance and failed to separate out these experimental effects from the P2, underscoring the importance of detailed topographical information for PCA (Chapman & McCrary, 1995). The timecourse of this factor is such that it could indeed account for some of the P300 in addition to the P2.

Factor 7 (P300 window) peaks at 352 ms and has a parietal maximum positive peak with a complementary frontal inferior negativity. At the parietal peak region, there is an attention effect (attend * stimulus * site, F[5, 75] = 5.269, p = .0126, e = .376) that is moderately present for standards (F[1, 75] = 6.049, p = .0443) but mostly for targets (F[1, 75] = 38.826, p = .0001).

This factor has the topography and time course of the P300 (Sutton & Ruchkin, 1984). As is expected for a P300 component, this factor is clearly enhanced to significant stimuli, namely the attended modality and targets. As previously reported, the amplitude of the P300 to targets in 50/50 oddball tasks is small (Duncan-Johnson & Donchin, 1977).

Factor 1 (Slow Wave window) peaks at 448 ms and has a broadly negative peak in the frontal half of the scalp and a broadly positive peak in the posterior half. There is an attention effect of increased positivity at the posterior dorsal peak (attend * stimulus * site, F[5, 75] = 11.599, p = .0002, e = .414) for standards (F[1, 75] = 40.011, p = .0001) and most especially targets (F[1, 75] = 208.069, p = .0001).

This factor has the proper topography and time course for the Slow Wave (Sutton & Ruchkin, 1984). As it should, the factor is responsive to significance, namely attended modality and target status.

Factor 2 (O-wave window) peaks at 824 ms. This factor shows an attention effect (attend * site, F[5, 75] = 7.211, p = .0033, e = .380) in which attended stimuli cause the anterior dorsal to become negative (F[1, 75] = 17.931, p = .0036) and the anterior ventral to go positive (F[1, 75] = 8.919, p = .0221). Factor 2 appears to be the O-wave, a late frontal negativity that is especially evoked by auditory stimuli (Rohrbaugh, Syndulko & Lindsley, 1979).

The correlations between factors may also be informative. A number of the factors were correlated over .3 The Slow Wave factor was correlated .47 with the O-wave factor, .35 with the P2 factor, .31 with the N1 factor, and .52 with the Nd factor. The O-wave factor was correlated with the P300 factor -.36. Finally, the P2 factor was correlated with the P300 factor .32. There was therefore a strong correlation between the slow wave and the Nd and O-wave factors. There was not, however, any notable correlation between the P300 and the Slow Wave factors despite their substantial overlap.

Extension of PCA

Although the Scree test has been found to be a generally reliable criteria for determining the number of factors to retain (Zwick & Velicer, 1986), it is still only a guideline. This point is of particular concern since the factor reflecting the bulk of the Nd, Factor 8, is both one of the final factors retained and has a multiphasic time course that could be due to merged components. In a post-hoc fashion, PCA was carried out arbitrarily retaining 12 factors. In order to compare the results, the correlation matrix of the factor scores (representing the distribution of the factors across the channels, conditions, and subjects) for the two solutions were computed. A factor was said to have replicated if it correlated with a new factor at least .70 (50% variance accounted for). The first four factors replicated at .99. Factors 6 (Tb) correlated at .83 and 7 (P300) at .92. Factors 5 and 9, both small factors, did not replicate. Factor 8 divided into three new factors, correlating .53, 52, and -.57, presumably below the .7 criteria due to their partition of the original variance.

This finding raises concern about the stability of the three new factors. An additional PCA was therefore carried out retaining 16 factors. Two of the three Nd factors replicated with correlations of .71 and .89 respectively. The seven other substantive factors also replicated at over .88 each. The other three factors neither replicated nor clearly split. Since the effect of retaining noise factors can be to degrade the resulting solution, the two reliable Nd factors of the 12 factor solution, rather than of the 16 factor solution, were used for subsequent examination.

The first (accounting for the Nde and Pd) has a biphasic pattern with an initial frontal negative peak at 128 ms followed by a positive peak at 184 ms (Figure 12). Amplitudes of this feature were enhanced for attended stimuli: attend * site, F(5, 75) = 6.344, p = .0081, e = .339. This enhancement was mostly due to a target effect: attend * stimulus * site, F(5, 75) = 4.902, p = .0196, e = .343.

The second (accounting for the Ndl) peaked at 292 ms with a frontal inferior negativity and a posterior superior positivity (Figure 13). This factor is larger to attended stimuli: attend * stimulus, F(5, 75) = 5.068, p = .0138, e = .385. There was a tendency for the feature to be overall more positive contralateral to the stimulus: field * hemisphere, F(1, 15) = 6.218, p = .0248.

Insert Figures 12-13 about here

Discussion of Auditory Analysis

This dataset makes it possible to evaluate the plausibility of the PCA factors as approximations to the latent components of the evoked potential. Each factor may be evaluated according to its time course, topography, and its responsiveness to experimental manipulations.

The P50 factor results must be seen as tentative in this dataset. The factor peaks at 53 ms which is in accordance with previous descriptions (Näätänen, 1992) and has a topography more clearly defined than that of the averaged data. On the other hand, its loadings start with stimulus onset suggesting that the PCA allocated variance to this factor that may be inappropriate. This factor also has a significant target effect that seems unreasonably early. Most importantly, this factor did not prove to be stable when additional factors were retained. Overall, these findings should be considered with caution, with the understanding that this dataset may not have had enough trials to properly resolve this early component.

The N1 factor appears to reflect the N1 component quite well. The factor has a topography and peak time that matches the topography and time course of the N1. The chief unexpected result is the biphasic nature of the N1 factor, with a peak of opposite polarity following the main deflection. It is uncertain whether this is a veridical reflection of the neurophysiological N1 or a statistical artifact. No such biphasic pattern is seen in MEG (magneto-encephalogram) recordings (Hari et al., 1989) but the relationship between ERP and ERF (event-related field) components is still being elucidated.

The Tb factor also seems plausible in terms of its time course and topography. The experimental effect was complicated by an interaction of field and hemisphere that makes it unclear whether it represents an attention or a target effect. It is possible that it is indeed enhanced to standards in which case the positive end of this component could be responsible for reports that the P2 (which it overlaps) is larger for standards (Alho, Tottola, Reinikainen, Sams & Näätänen, 1987; Curry et al., 1983; Hackley et al., 1990; Vaughan, Ritter & Simson, 1980). The strong right-lateralization of Tb is intriguing. Perhaps this is related to right-lateralization of tone processing as opposed to verbal sounds, although previous efforts to find such lateralized effects have failed (Friedman, Simson, Ritter & Rapin, 1975; Galambos, Benson, Smith, Schulman-Galambos & Osier, 1975).

The P2 factor seems to have a plausible time course and topography, although like the N1 it has an unexpected biphasic pattern. It is possible that the N1 and the P2 factors have misallocated some variance with each other due to similar spatial and experimental variance and partial temporal overlap (Wood & McCarthy, 1984). On the other hand, the neurophysiological events may not in fact be monophasic.

The PCA seems to separate the P300 from the coincident Slow Wave. The parietal-central location of its positive peak, its latency, and its responsiveness to target significance all indicate its identity as a P300. This component is not evident in the grand average plots, probably since the P300 target effect is minimal in a 50/50 oddball (Duncan-Johnson & Donchin, 1977), making it a true latent variable. Without the PCA results, the large Slow Wave might have been mistaken for a P300. The PCA analysis also indicated the

P300 has an interesting contralateral response to the stimuli, although this could be the result of misallocation of variance from the overlapping Slow Wave.

The time course and modulation by attention suggest the Nde may be a unique component. The separation of this factor from the N1 factor, with a distinct waveform and topography, may support the contention that the Nde is not just an enhancement of the N1. Although the original solution captured both the Nde and Ndl in a single factor, the extended solutions split them into separate factors with quite distinct topographies. The Nde factor had a surprising target effect that was not evident in the windowed analyses and may be artifactual, due to overlap with the Tb feature, for example.

An unresolved issue is the time course of the underlying processing negativity (PN) that gives rise to the Nd. Since PCA fits the data to temporally-fixed latent waveforms, it is not suited to resolving features that change in latency or duration. The variance due to small changes in time course can be too small to distinguish from error variance. Thus, while this analysis suggests there is a difference in amplitude of the PN between attended and unattended stimuli, it does not indicate the nature of any time course differences.

The Slow Wave factor is a quite reasonable match to the component in terms of time course, topography, and responsiveness to experimental manipulations. An interesting aspect to these findings is its responsiveness to field of presentation. Not only is it not symmetrical, the usual report, but it is enhanced for left field presentations (which are mostly processed by the right hemisphere). This is interesting in view of the right hemisphere's special role in orienting and attention (Heilman & Watson, 1989; Tucker & Williamson, 1984).

Finally, the O-wave factor is a good example of the ability of PCA to detect subtle features of the data. In the difference wave between attended and unattended auditory stimuli, the O-wave is difficult to distinguish from the effects of the P300. The O-wave factor, on the other hand, displays a distinct waveform, topography, and responsiveness to attention.

Dipole Modeling

One advantage of PCA decomposition of waveforms is that it can potentially simplify dipole modeling. One approximation is to model a factor as two equivalent dipoles, one in either hemisphere. By potentially removing most overlapping activity, it simplifies the modeling process and minimizes errors that can arise when multiple dipoles are fitted (Zhang & Jewett, 1993) or when the number of dipoles is misspecified (Achim et al., 1991). An ERP feature may be generated by multiple widely separated sources that vary in synchrony (thus loading on the same factor) but the number of spatial arrangements that would result in a single equivalent dipole would seem to be limited. Solutions that cannot be modelled with a single pair of hemispheric dipoles are uninterpretable as they may either arise from multiple synchronous sources or from misallocation of variance at the PCA step. Ideally, convergent validity from neuroanatomy or rCBF studies is desirable as well. Note, recent efforts in cross-registration of ERP and rCBF measures have provided additional support for localization algorithms (Heinze et al., 1994).

Dipoles were fit to the N1, Nde, and Ndl factors of the auditory dataset using BESA 2.2 (Scherg & Berg, 1990; Scherg & Picton, 1991) using the mean factor scores of all auditory conditions collapsed together. The two factors were modeled with one dipole in each hemisphere with locations and orientations constrained to be symmetric. To minimize interactions between the dipoles, the energy minimum criteria was set at 20%. Since the stimuli were auditory, an initial placement of the supratemporal plane was utilized. The BESA program was then used to perform a moving dipole fit in which the dipole locations and orientations are iteratively shifted to improve the fit to the observed data. Over the period of -184 to 840 ms, the model for the N1 factor explained 97.36% of the variance and placed the dipole on the supratemporal plane (Figure 14). This result is consistent with previous dipole modeling efforts (Scherg & Von Cramon, 1985).

BESA was then applied to the Nde and Ndl factors from the 12-factor solution. A similar procedure resulted in a model that explained 88.1% of the variance for the Nde/Pd factor and placed the source in the walls of the medial cortex (Figure 15). Frontal and occipital starting locations yielded identical results. The dipole site appears to be near the proposed anterior attention system but could also be consistent with the supplementary motor area (SMA). Diffuse areas of activation are modeled by equivalent point dipoles with the same orientation but deeper position (Scherg, 1990). This solution could therefore also reflect a broader region of activation on the dorsolateral surface. However, the Nde (and Ndl) are attenuated by dorsolateral prefrontal lesions bilaterally following unilateral lesions (Knight, Hillyard, Woods & Neville, 1981), suggesting that this region regulates the source region rather than it being the source itself (Näätänen, 1985). The Roland (1982) study supports both possibilities as it found increased activation for both the medial and lateral surface for attention to auditory stimuli relative to visual and somatosensory stimuli.

By contrast, the Ndl factor was fit by point dipoles explaining 93.42% of the variance that were positioned deep below the central fissure (Figure 16). This solution is therefore consistent with a broad superior parietal activation which is another area implicated in attention (Posner, Walker, Friedrich & Rafal, 1987). On the other hand, this source does not readily match active regions in the available rCBF study (Roland, 1982). More precise localization would require ERP and positron emission tomography (PET) data from the same subjects, perhaps cross-registered using magnetic resonance imaging (MRI) scans.

Finally, the Tb factor was fit by point dipoles explaining 82.39% of the variance positioned under the frontal cortex (Figure 17). The equivalent dipole position is unlikely to be the actual source but is compatible with a broader activation over the frontal cortex. This solution is particularly intriguing because this feature is normally interpreted as arising from lateral temporal cortex (Wolpaw & Penry, 1975). However, this feature was shown to be sensitive to attention in this paradigm and is strongly right-lateralized, much as the Roland study found an enhanced right prefrontal activation in the auditory attention condition.

Insert Figures 14-17 about here

One weakness of dipole modeling as generally reported is a lack of statistical analysis to verify whether differing solutions are indeed unlikely to arise from chance variation. A t-test procedure was therefore developed to test whether the solutions for the Nd factors are indeed significantly different from the N1 solution. The t-test procedure consists of comparing the difference between two group means to the variation within each group (pooled). The same logic can be applied to the two dipole models of the two factors. The distance between two locations can be calculated by using the Pythagorean formula, taking the square root of the sum of the squared differences in each of the three dimensions. The within group variation can be calculated by modeling the factor for each subject individually and calculating the distance between the resulting location and the group (grand average) mean. Since there is no guarantee that the within group population variances for the two groups are the same, an independent measures t-test was utilized. A similar procedure can be applied to the orientations of the source solutions. While it is likely that the population variation about the mean location is not symmetrically distributed, violating assumptions of normality, this procedure is an improvement over simple visual inspection.

This test indicated that the Nde factor solution differed significantly from that of the N1 factor solution in location ($t[30] = 4.13$, $p < .01$) but not orientation ($t[30] = 1.29$, $p > .05$). The Ndl factor solution location, on the other hand, did not differ significantly ($t[30] = 1.94$, $p > .05$) although, its orientation did indeed differ ($t[30] = 3.22$, $p < .01$).

Although one might be concerned that the use of an average reference could produce “ghost fields” in vertically oriented sources (Desmedt, Chalklin & Tomberg, 1990) that could somehow produce a tangential solution for the Nde, this is not a substantive issue. BESA has been extensively tested with auditory dipoles (Scherg, Vajsar & Picton, 1989; Scherg & Von Cramon, 1986) and has not been reported to produce such results in the past (given that all BESA analyses automatically use the average reference). The tangential nature of the Nde dipole solution reflects the scalp distribution which has an oval negative region extended laterally in the anterior and a positive region at the same level in the posterior. By contrast, the N1 has a similar distribution on its negative end but its positive region is along the inferior surface, constituting a vertical orientation. In any case, one would not expect the Nde feature to be affected by ghost fields but not the N1 feature since the N1 is vertically oriented.

Visual evoked potential

The visual condition was examined chiefly to determine whether any of the attention effects seen in the auditory analyses were present as well. Visual inspection of the data revealed a general amplitude modulation, perhaps due to defocusing by the subjects, but nothing analogous to the Nd effects (Figure 18). A PCA produced an O-wave factor but nothing similar to the Nd or Tb factors. Since the O-wave has too long a latency to be involved in attentional selection, it was not further analyzed.

Insert Figure 18 about here

General Discussion

Although the use of a relatively long ISI (3.5 seconds) might raise concern about to what extent the subjects are focusing attention on the auditory channel, the evoked potentials clearly contain the same Nde and Ndl effects noted in other studies using shorter ISIs. The long ISI is likely the reason why more subtle attentional effects were not seen, such as N1 modulation or the 20-50 effect (Woldorff & Hillyard, 1991).

This report demonstrates that PCA and dipole modeling techniques like BESA may have complementary strengths. PCA has the strength of utilizing variance from subjects and conditions, in addition to the spatial and temporal variance used by dipole fits, to determine the dimensionality of the data (even the PCA module in BESA operates only on spatial and temporal variance). PCA results also have the strength that the technique incorporates minimal assumptions about the spatial distribution of components. On the other hand, dipole models provide rigor to inferences about source localization and take into account information about the physical structure of the head and brain. As this paper demonstrates, PCA is useful for determining the dimensional nature of an ERP dataset and simplifying the dipole fitting procedure.

The use of PCA and dipole modeling, both methods with notable caveats as discussed earlier, may cause some discomfort. The key consideration with these techniques, as with any other, is not whether they are perfect but whether they offer additional or improved information over existing methods. In both cases the answer is affirmative. As McCarthy and Woods themselves note, misallocation of variance is a problem for ERP analysis in general, not just for PCA. For decomposing sets of evoked potentials, PCA has the advantage of taking the entire dataset into account (thousands of observations), a task that is beyond the capability of visual inspection. Similarly, researchers frequently speculate about the source of ERP components; for all the limitations of dipole modeling techniques, they offer increased rigor and sophistication over simple visual inspection. Like all scientific reports, these findings are meant to constitute not a final answer but an additional increment in our understanding that guides further investigations. Ultimately, the judgment of the validity of these findings, like with all brain imaging findings, must await demonstration of convergent validity. The observed convergences between these results and the Roland rCBF study provide an initial effort in this direction.

While it has been clear that the attentional effect found by subtracting evoked potentials to unattended standards from attended standards has multiple sources, their nature and number has been uncertain. The present results suggest that latent variable analysis with a dense sensor array may provide a new perspective on the nature of the Nd attentional effects. This analysis suggests there are at least four notable contributors, namely the Nde/Pd, the Ndl, the Tb, and the O-wave.

Contrary to prior reports (Vaughan & Ritter, 1970; Woods et al., 1992), the present data suggests that the Nde may emanate from the anterior medial cortex rather than auditory cortex. This finding is consistent with reports that a portion of the auditory N1 originates in frontal, possibly cingulate, cortex (Alcaini, Giard, Thévenet & Pernier, 1994; Giard et al., 1994) and that the N1 consists of both a portion from the auditory cortex and a portion that emanates from a more dorsal source (Hari, Kaila, Katila, Tuomisto & Varpula, 1982). This source could be the superior medial region implicated by rCBF (Roland, 1982) or, taking into account measurement error, the anterior cingulate. This result supports the notion that this feature reflects a secondary process rather than a portion of the main sensory processing pathway.

The source of the Ndl is less clear but it does not appear to have a frontal source like that of the Nde. Since the source location of the Ndl factor did not differ significantly from the superior temporal plane, it is possible that it does emanate from that region. Indeed, a MEG study has found an Nd source at the Ndl latency in the auditory cortex (Arthur, Lewis, Medvick & Flynn, 1991; Hari et al., 1989).

Although the Tb component has been consistently interpreted as arising in the lateral temporal auditory association cortex (Wolpaw & Penry, 1975), this analysis suggests instead a source in the prefrontal cortex. Intriguingly, in Roland’s study, there was attentional enhancement to the right midfrontal anterior region (roughly area 46) just as the Tb feature is heavily right-lateralized. This enhancement appeared only for attention to the auditory modality, not to visual or somatosensory. Cross-registration will be required to test this hypothesis.

The final attention-modulated component was the O-wave. The late time course of this feature, extending beyond the recording epoch, reinforces the point that the attention-related effects found in rCBF studies cannot be assumed to be related to the selection process without temporal information. Unfortunately, this factor was poorly modeled, with 38.5% of the variance remaining, and therefore the location of the dipoles should not be further interpreted. Visual inspection of the factor’s topography suggests that it has an unstable topography across conditions. It seems likely that this factor confounds multiple sources of slow shifts, making it difficult to interpret.

The dipole locations of the Nde and the Tb, if correct, were quite intriguing. Nde appears to arise from the vicinity of the SMA, suggesting that the motor system might receive attentional modulation even before the sensory information is filtered. Indeed, the lateral premotor cortex of monkeys contains cells that start responding as soon as 60 ms after a visual signal (Weinrich, Wise & Mauritz, 1984). It is reasonable that the motor system might receive preliminary information about whether sensory information is arriving in an attended channel; the output system could be considered a parallel stream that receives separate attentional modulation. Tb appears to arise from the right prefrontal region and could represent activation of some type of working memory (Goldman-Rakic, 1990) or episodic memory (Tulving, Kapur, Craik, Moscovitch & Houle, 1994). If this component is indeed displaying a target effect (an enhancement to standards) this effect would be compatible with this account.

Both the Nde and Tb localizations corresponded well to activations seen in Roland's rCBF data. On the other hand, they represent amodal cortex that would be expected to respond to visual stimuli as well. There do not appear to be any features in visual evoked potentials comparable to the Tb. As for the Nde, amodal frontal midline negativities have been identified but are not convincing candidates for a visual Nde equivalent. The error-related negativity (ERN) (Falkenstein, Hohnsbein, Hoormann & Blanke, 1990; Gehring, Goss, Coles, Meyer & Donchin, 1993) appears somewhat later than the Nd features of the present dataset and has been fit to a deeper, more frontal dipole (Dehaene, Posner & Tucker, 1994). Likewise, the N2b (Pritchard, Shappell & Brandt, 1991) has been related to attentional mechanisms but typically has a later latency than the Nde.

One possibility is that the process indexed by the Nd is amodal but that the visual stimuli are not evoking it. For example, it may be that auditory stimuli, which appear to emanate from positions 90 degrees from frontal fixation, evoke more preparation in the motor pathways and/or more spatial processing. It may even be that although this cortex is amodal, auditory information has a stronger influence over these systems than visual.

Another possibility is that the Nd reflects an amodal attentional function that is not being modulated by current visual paradigms. For example, since intermodal attention studies generally require subjects to maintain visual fixation to minimize motion artifacts, it is possible that the visual inattention conditions are not comparable to the auditory inattention conditions. If the subjects were in effect attending to the visual modality in all conditions, no visual attention effects would be seen in the evoked potentials. Although no Nd factor was found in the PCA of the visual data, it could mean that the individual difference and spatial variance were insufficient alone to disentangle this feature. In any case, Roland's rCBF data also show a mostly auditory specific attention effect for these two regions, supporting these localizations for these components.

This discussion raises the question of what kind of activations are relevant to issues of attention. On purist grounds one might prefer to isolate regions that are the direct "cause" of attentional selection, whether in a general purpose or task-specific sense (c.f., Posner & Driver, 1992). However, the site of an attentional effect may not necessarily be its source (Posner, 1995). Given the growing consensus that attentional processes involve a distributed process across a number of regions, albeit with different versions (Allport, 1993; Mesulam, 1990; Posner & Petersen, 1990), it may be best to define attentional processes as the sum of differences between the states of attending and not attending. Put in this way, it is the task of cognitive neuroscience to characterize all such differences and then to identify the contributions and causal links of each element.

Consideration of these results raises a more general question of how a cognitive neuroscientist should approach evoked potential data. Should one think in terms of psychophysiological components such as the Nde and Ndl or should one think in terms of neural structures such as the anterior cingulate or inferior parietal? As localization techniques improve, could one ignore the literature on ERP components in favor of brain imaging studies when designing experiments? At this point, the conservative response would be that both are necessary. In truth, every method has associated strengths and weaknesses and it would be naive to expect that a given brain imaging method, whether ERP or PET or fMRI, can report all brain activity. ERP components provide labels for those aspects of brain activity that can be readily detected by this particular methodology and a shorthand for the bodies of research they have garnered. Moreover, some components (such as the P300) could represent distributed systems or events rather than the activity of a discrete region. As the rCBF literature matures, corresponding limitations are being recognized and is producing a methodologically bounded literature that could eventually produce a similar shorthand.

In conclusion, this analysis suggests that a major aspect of auditory attention, as indexed by ERPs, is related to a secondary process. Further progress on this issue will require the application of modern cerebral blood flow techniques to the intermodal attention paradigm, cross-registered with ERP data to provide time course information. Methodologically, this paper demonstrates how the combination of high-density topographical information and statistical analysis can facilitate the cross-registration of rCBF and ERP data.

Methods

Subjects

Subjects were 16 right-handed undergraduate psychology students (10 M, 6 F; 22.4 years), participating for course credit.

Apparatus

The EEG was recorded using the Geodesic Sensor Net, a network of 57 Ag/AgCl sponge sensors organized by elastic threads into a geodesic tension structure (Tucker, 1993). Seven additional Ag/AgCl disk sensors were applied in the following locations: one at each external canthus, one at the center of each infraorbital region, one at the glabella and one at the center of each mastoid bone (see Figure 19 for general layout of sensors). The right mastoid was used as reference sensor. The EEG was amplified and filtered with a 0.15 Hz to 50 Hz (3 dB attenuation) bandpass, and a 60 hz notch filter. The signals were digitized at

250 samples per second using a National Instruments NB-MIO16 16-bit analog to digital converter installed in a Macintosh II computer. The EEG signals were transferred to computer memory using a National Instruments Direct Memory Access card, then stored to magnetic disk during the inter-trial interval. The Macintosh II computer controlled the data acquisition and stimulus display using the Oregon Brain Electrophysiology Laboratory's EGIS (Electrophysiological Graphical Interface System) software.

Insert Figure 19 about here

Stimuli and Tasks

Visual stimuli were the digits '2' and '4' (about .2 degrees in size) presented to the right and left visual fields at about 7.5 degrees. Auditory stimuli were 440 hz and 1245 hz sine waves presented to the right and left ears. The stimuli were matched for apparent loudness. The exact dB is not available unfortunately but is estimated to have been in the range of 60-80 dB. The interstimulus interval (ISI) was approximately 3.5 s with a random variability of about +/- 250 ms to make exact stimulus onset unpredictable. For each experiment run, one of the digits and one of the tones were designated as targets; the remaining digit and tone were designated as nontargets. Thus there were three stimulus factors with two levels each: Modality (Visual, Auditory), Field (Left, Right), Stimulus Type (Target, Nontarget). On each trial the Modality, Field, and Stimulus Type was randomly selected without replacement from an equiprobable pool of trial types.

There were two task types, auditory selection and visual selection. In the auditory selection task subjects were to silently count the number of auditory target stimuli presented in the block, regardless of the ear of presentation, and ignore the auditory nontarget and both visual stimuli. In the visual selection task subjects were to count the number of visual targets presented in the block, regardless of visual filed of presentation, and ignore the visual nontarget and both auditory stimuli. Each subject performed two blocks of each selection task, counterbalanced across subjects for order effects.

Artifact Rejection and Averaging

The raw subject data files were passed through a computerized artifact detection algorithm. Trials containing blinks (defined as 30 μv difference between vertical EOG channels) were dropped. Channels were marked as bad if they changed more than 50 μv between samples or exceeded +/-100 μv. Trials with 10 or more bad channels were discarded. If a trial was retained, only the defective channels were discarded. Channels that were wholly dropped from subject averages (1.5% of the total waveforms) were replaced with estimated waveforms derived by regression equations from neighboring channels. Correlations between predicted and observed values (mean across time points) range from .70 (channel 56) to .88 (channel 34).

The raw trials were averaged for each subject for each experimental cell. The subject averages file was rereferenced from the right mastoid to an average reference representation. The subject averages were also digitally filtered with a 30 hz lowpass filter to remove residual 67 hz monitor refresh artifact. The data were also baseline corrected for the prestimulus interval. A grand average file was created by averaging across the subject averages for each experimental cell.

Given the ongoing controversy over reference technique, it would be desirable to justify the use of the average reference. Waveform recordings generally consist of the voltage difference between the recording site and a common reference site. To the extent that the reference site is not inactive, all the recordings will include misleading activity that is actually due to the reference site (Nunez, 1981). It is unlikely that the mastoid site is inactive since it lies close to the brain.

The average reference is an effort to remove reference site artifacts (Skrandies & Lehmann, 1982). It is based on the principle that a full sampling of the head potentials will average to zero (Bertrand, Perrin &

Pernier, 1985). In this ideal case, the average would only deviate from zero due to reference site artifact. One could therefore correct for this error by subtracting this deviation from the recordings. The average reference is flawed to the extent that the head potentials are not fully sampled, particularly the underside of the head, and therefore do not truly average to zero (Desmedt et al., 1990). Thus, both reference options suffer from weaknesses in their fundamental assumptions.

Although it is unknown which set of assumptions is more accurate, the average reference was chosen since it ensures the entire analysis is carried out in the same reference space. BESA average references all data since there is no place on the head model that is insulated from potential fields and is therefore guaranteed to be inactive. Likewise, the correlation and covariance matrices used for PCA essentially average references the data since it sets the mean of each timepoint to zero (albeit across the entire dataset rather than separately for each set of electrode recordings). Indeed, a PCA carried out on an average mastoid version (available on request) produced similar results.

References

Achim, A., Richer, F., & Saint-Hilaire, J.-M. (1991). Methodological considerations for the evaluation of spatio-temporal source models. Electroencephalography and Clinical Neurophysiology, 79, 227-240.

Alcaini, M., Giard, M. H., Thévenet, M., & Pernier, J. (1994). Two separate frontal components in the N1 wave of the human auditory evoked response. Psychophysiology, 31, 611-615.

Alho, K., Tottola, K., Reinikainen, K., Sams, M., & Näätänen, R. (1987). Brain mechanisms of selective listening reflected by event-related potentials. Electroencephalography and Clinical Neurophysiology, 68, 459-470.

Alho, K., Woods, D. L., Algazi, A., & Näätänen, R. (1992). Intermodal selective attention. II. Effects of attentional load on processing of auditory and visual stimuli in central space. Electroencephalography and Clinical Neurophysiology, 82, 356-368.

Allport, A. (1993). Attention and control: Have we been asking the wrong questions? A critical review of twenty-five years. In D. E. Meyer & S. Kornblum (Eds.), Attention and performance, (Vol. XIV, pp. 183-218). Cambridge, Mass: MIT Press.

Arthur, D. L., Lewis, P. S., Medvick, P. A., & Flynn, E. R. (1991). A neuromagnetic study of selective auditory attention. Electroencephalography and Clinical Neurophysiology, 78, 348-360.

Bertrand, O., Perrin, F., & Pernier, J. (1985). A theoretical justification of the average reference in topographic evoked potential studies. Electroencephalography and Clinical Neurophysiology, 62, 462-464.

Broadbent, D. E. (1958). Perception and communication. New York: Pergamon.

Cattell, R. B. (1966). The scree test for the number of factors. Multivariate Behavioral Research, 1, 245-276.

Cattell, R. B., & Jaspers, J. (1967). A general plasmode (No. 3010-5-2) for factor analytic exercises and research. Multivariate Behavioral Research Monographs, 67-3, 1-212.

Chapman, R. M., & McCrary, J. W. (1995). EP component identification and measurement by principal components analysis. Brain and Cognition, 27, 288-310.

Curran, T., Tucker, D. M., Kutas, M., & Posner, M. I. (1993). Topography of the N400: Brain electrical activity reflecting semantic expectation. Electroencephalography and Clinical Neurophysiology, 88(3), 188-209.

Curry, S. H., Cooper, R., McCallum, W. C., Pocock, P. V., Papakostopoulos, D., Skidmore, S., & Newton, P. (1983). The principal components of auditory target detection. In A. W. K. Gaillard & W. Ritter (Eds.), Tutorials in ERP research: Endogenous components, (pp. 79-117). Amsterdam: North-Holland Publishing Company.

Deacon, D., Breton, F., Ritter, W., & Vaughan, H. G. (1991). The relationship between N2 and N400: Scalp distribution, stimulus probability, and task relevance. Psychophysiology, 28(2), 185-200.

Dehaene, S., Posner, M. I., & Tucker, D. M. (1994). Localization of a neural system for error detection and compensation. Psychological Science, 5(5), 303-305.

Desmedt, J. E., Chalklin, V., & Tomberg, C. (1990). Emulation of somatosensory evoked potential (SEP) components with the 3-shell head model and the problem of 'ghost potential fields' when using an average reference in brain mapping. Electroencephalography and Clinical Neurophysiology, 77, 243-258.

Deutsch, J. A., & Deutsch, D. (1963). Attention: Some theoretical considerations. Psychological Review, 70, 80-90.

Dien, J., & Tucker, D. M. (in submission). Analyzing superposition: Statistical decomposition of the visual event-related potential in semantic processing.

Donchin, E., & Heffley, E. (1979). Multivariate analysis of event-related potential data: A tutorial review. In D. Otto (Ed.), Multidisciplinary perspectives in event-related potential research (EPA 600/9-77-043), (pp. 555-572). Washington, DC: U.S. Government Printing Office.

Duncan-Johnson, C. C., & Donchin, E. (1977). On quantifying surprise: The variation of event-related potentials with subjective probability. Psychophysiology, 14(3), 456-467.

Falkenstein, M., Hohnsbein, J., Hoormann, J., & Blanke, L. (1990). Effects of errors in choice reaction time tasks on the ERP under focused and divided attention. In C. H. M. Brunia, A. W. K. Gaillard, & A. Kok (Eds.), Psychophysiological brain research, (pp. 192-195). Tilburg, The Netherlands: Tilburg University Press.

Friedman, D., Simson, R., Ritter, W., & Rapin, I. (1975). Cortical evoked potentials elicited by real speech words and human sounds. Electroencephalography and Clinical Neurophysiology, 38, 13-19.

Galambos, R., Benson, P., Smith, T. S., Schulman-Galambos, C., & Osier, H. (1975). On hemispheric differences in evoked potentials to speech stimuli. Electroencephalography and Clinical Neurophysiology, 39, 279-283.

Gehring, W. J., Goss, B., Coles, M. G. H., Meyer, D. E., & Donchin, E. (1993). A neural system for error detection and compensation. Psychological Science, 4, 385-390.

Geisser, S., & Greenhouse, S. W. (1958). An extension of Box's results on the use of the F distribution in multivariate analysis. Annals of Mathematical Statistics, 29, 885-891.

Giard, M. H., Perrin, F., Echallier, J. F., Thevenet, M., Froment, J. C., & Pernier, J. (1994). Dissociation of temporal and frontal components in the human auditory N1 wave: a scalp current density and dipole model analysis. Electroencephalography and Clinical Neurophysiology, 92, 238-252.

Giard, M. H., Perrin, F., Pernier, J., & Peronnet, F. (1988). Several attention-related wave forms in auditory areas: A topographic study. Electroencephalography and Clinical Neurophysiology, 69, 371-384.

Goldman-Rakic, P. S. (1990). Cellular and circuit basis of working memory in prefrontal cortex of nonhuman primates. Progress in Brain Research, 85, 325-336.

Gorsuch, R. L. (1983). Factor analysis (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum Associates.

Hackley, S. A., Woldorff, M., & Hillyard, S. A. (1990). Cross-modal selective attention effects on retinal, myogenic, brainstem, and cerebral evoked potentials. Psychophysiology, 27(2), 195-208.

Hansen, J. C., & Hillyard, S. A. (1980). Endogenous brain potentials associated with selective auditory attention. Electroencephalography and Clinical Neurophysiology, 49, 277-290.

Hansen, J. C., & Hillyard, S. A. (1984). Effects of stimulus rate and attribute cuing on event-related potentials during auditory attention. Psychophysiology, 21, 394-405.

Hari, R., Hämäläinen, M., Kaukoranta, E., Mäkelä, J., Joutsiniemi, S. L., & Tiihonen, J. (1989). Selective listening modifies activity of the human auditory cortex. Experimental Brain Research, 74, 463-470.

Hari, R., Kaila, K., Katila, T., Tuomisto, T., & Varpula, T. (1982). Interstimulus interval dependence of the auditory vertex response and its magnetic counterpart: implications for their neural generation. Electroencephalography and Clinical Neurophysiology, 54, 561-569.

Heilman, K. M., & Watson, R. T. (1989). Arousal and emotions. In F. Boller & J. Grafman (Eds.), Handbook of Neuropsychology, Vol. 3, (pp. 403-417): Elsevier Science Publishers.

Heinze, H. J., Mangun, G. R., Burchert, W., Hinrichs, H., Scholz, M., Munte, T. F., Gos, A., Scherg, M., Johannes, S., Hundeshagen, H., Gazzaniga, M. S., & Hillyard, S. A. (1994). Combined spatial and temporal imaging of brain activity during visual selective attention in humans. Nature, 372, 543-546.

Hillyard, S. A., Hink, R. F., Schwent, V. L., & Picton, T. W. (1973). Electrical signs of selective attention in the human brain. Science, 182, 177-180.

Knight, R. T., Hillyard, S. A., Woods, D. L., & Neville, H. J. (1981). The effects of frontal cortex lesions on event-related potentials during auditory selective attention. Electroencephalography and Clinical Neurophysiology, 52, 571-582.

Mesulam, M. (1990). Large-scale neurocognitive networks and distributed processing for attention, language, and memory. Annals of Neurology, 28, 597-613.

Möcks, J., & Verleger, R. (1986). Principal component analysis of event-related potentials: A note on misallocation of variance. Electroencephalography and Clinical Neurophysiology, 65, 393-398.

Mosher, J. C. (1992). Multiple dipole modeling and localization from spatio-temporal MEG data. IEEE Transactions on Biomedical Engineering, 39(6), 541-557.

Näätänen, R. (1985). Selective attention and stimulus processing: Reflections in event-related potentials, magnetoencephalogram, and regional cerebral blood flow. In M. I. Posner & O. S. Marin (Eds.), Attention and Performance, (Vol. XI, pp. 355-373). New York: Erlbaum.

Näätänen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. Behavioral and Brain Sciences, 13, 201-288.

Näätänen, R. (1992). Attention and brain function. Hillsdale, NJ: Lawrence Erlbaum Associates.

Näätänen, R., Gaillard, A. W. K., & Mäntysalo, S. (1978). Early selective attention effect on evoked potential reinterpreted. Acta Psychologica, 42, 313-329.

Näätänen, R., & Picton, T. (1987). The N1 wave of the human electric and magnetic response to sound: A review and an analysis of the component structure. Psychophysiology, 24(4), 375-425.

Nunez, P. L. (1981). Electric fields of the brain: The neurophysics of EEG. New York: Oxford University Press.

Nunez, P. L. (1990). Physical principles and neurophysiological mechanisms underlying event-related potentials. In J. W. Rohrbaugh, R. Parasuraman, & R. Johnson (Eds.), Event-related brain potentials: Basic issues and applications, (pp. 19-36). New York: Oxford University Press.

Polich, J. (1985). Semantic categorization and event-related potentials. Brain and Cognition, 26, 304-321.

Posner, M. I. (1995). Attention in cognitive neuroscience: An overview. In M. S. Gazzaniga (Ed.), The cognitive neurosciences, (pp. 615-624). Cambridge, Mass.: MIT Press.

Posner, M. I., & Driver, J. (1992). The neurobiology of selective attention. Current Opinion in Neurobiology, 2, 165-169.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. Annual Review of Neuroscience, 13, 25-42.

Posner, M. I., Walker, J. A., Friedrich, F. A., & Rafal, R. D. (1987). How do the parietal lobes direct covert attention? Neuropsychologia, 25(1A), 135-145.

Pritchard, W. S., Shappell, S. A., & Brandt, M. E. (1991). Psychophysiology of N200/N400: A review and classification scheme. Advances in Psychophysiology, 4, 43-106.

Rohrbaugh, J. W., Syndulko, K., & Lindsley, D. B. (1979). Cortical slow negative waves following non-paired stimuli: Effects of modality, intensity and rate of stimulation. <u>Electroencephalography and Clinical Neurophysiology, 46</u>, 416-427.

Roland, P. E. (1982). Cortical regulation of selective attention in man. A regional cerebral blood flow study. <u>Journal of Neurophysiology, 48</u>(5), 1059-1078.

Roland, P. E. (1993). <u>Brain Activation</u>. New York: Wiley.

Scherg, M. (1990). Fundamentals of dipole source analysis. In F. Grandori & G. L. Romani (Eds.), <u>Auditory evoked magnetic fields and potentials</u>, (Vol. 6, pp. 1-30). New York: Karger.

Scherg, M., & Berg, P. (1990). <u>BESA - Brain electric source analysis handbook</u>. Munich: Max-Planck Institute for Psychiatry.

Scherg, M., & Picton, T. W. (1991). Separation and identification of event-related potential components by brain electric source analysis. In C. H. M. Brunia, G. Mulder, & M. N. Verbaten (Eds.), <u>Event-related brain research. Electroencephalography and Clinical Neurophysiology, supplement 42</u>, (pp. 24-37). Amsterdam: Elsevier.

Scherg, M., Vajsar, J., & Picton, T. W. (1989). A source analysis of the late human auditory evoked potentials. <u>Journal of Cognitive Neuroscience, 1</u>(4), 336-355.

Scherg, M., & Von Cramon, D. (1985). Two bilateral sources of the late AEP as identified by a spatio-temporal dipole model. <u>Electroencephalography and Clinical Neurophysiology, 62</u>, 32-44.

Scherg, M., & Von Cramon, D. (1986). Evoked dipole source potentials of the human auditory cortex. <u>Electroencephalography and Clinical Neurophysiology, 65</u>, 344-360.

Skrandies, W., & Lehmann, D. (1982). Spatial principal components of multichannel maps evoked by lateral visual half-field stimuli. <u>Electroencephalography and Clinical Neurophysiology, 54</u>, 662-667.

Squires, N. K., Squires, K. C., & Hillyard, S. A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. Electroencephalography and Clinical Neurophysiology, 38, 387-401.

Sutton, S., & Ruchkin, D. S. (1984). The late positive complex: Advances and new problems. Annals of the New York Academy of Sciences, 425, 1-23.

Teder, W., Alho, K., Reinikainen, K., & Näätänen, R. (1993). Interstimulus interval and the selective-attention effect on auditory ERPs: "N1 enhancement" versus processing negativity. Psychophysiology, 30, 71-81.

Tucker, D. M. (1993). Spatial sampling of head electrical fields: the geodesic sensor net. Electroencephalography and Clinical Neurophysiology, 87(3), 154-163.

Tucker, D. M., & Williamson, P. A. (1984). Asymmetric neural control systems in human self-regulation. Psychological Review, 91(2), 185-215.

Tulving, E., Kapur, S., Craik, F. I. M., Moscovitch, M., & Houle, S. (1994). Hemispheric encoding/retrieval asymmetry in episodic memory: positron emission tomography findings. Proceedings of the National Academy of Sciences, USA, 91, 2016-2020.

Vaughan, H., & Ritter, W. (1970). The sources of auditory evoked responses recorded from the human scalp. Electroencephalography and Clinical Neurophysiology, 28, 360-367.

Vaughan, H. G., Ritter, W., & Simson, R. (1980). Topographic analysis of auditory event-related potentials. In H. H. Kornhuber & L. Deecke (Eds.), Motivation, motor and sensory processes of the brain: Electrical potentials, behaviour and clinical use, (Vol. 54, pp. 279-285). Amsterdam: Elsevier.

Weinrich, M., Wise, S. P., & Mauritz, K.-H. (1984). A neurophysiological study of the premotor cortex of the monkey. Brain, 107, 385-414.

Woldorff, M. G., & Hillyard, S. A. (1991). Modulation of early auditory processing during selective listening to rapidly presented tones. Electroencephalography and Clinical Neurophysiology, 79, 170-191.

Wolpaw, J. R., & Penry, J. K. (1975). A temporal component of the auditory evoked response. Electroencephalography and Clinical Neurophysiology, 39, 609-620.

Wood, C. C., & McCarthy, G. (1984). Principal component analysis of event-related potentials: Simulation studies demonstrate misallocation of variance across components. Electroencephalography and Clinical Neurophysiology, 59, 249-260.

Wood, C. C., & Wolpaw, J. R. (1982). Scalp distribution of human auditory evoked potentials. II. Evidence for overlapping sources and involvement of auditory cortex. Electroencephalography and Clinical Neurophysiology, 54, 25-38.

Woods, D. L. (1990). The physiological basis of selective attention: Implications of event-related potential studies. In J. W. Rohrbaugh, R. Parasuraman, & R. Johnson (Eds.), Event-related brain potentials: Basic issues and applications, (pp. 178-209). New York: Oxford University Press.

Woods, D. L., Alho, K., & Algazi, A. (1992). Intermodal selective attention. I. Effects on event-related potentials to lateralized auditory and visual stimuli. Electroencephalography and Clinical Neurophysiology, 82, 341-355.

Woods, D. L., Alho, K., & Algazi, A. (1994). Stages of auditory feature conjunction: An event-related brain potential study. Journal of Experimental Psychology: Human Perception and Performance, 20(1), 81-94.

Zhang, Z., & Jewett, D. L. (1993). Insidious errors in dipole localization parameters at a single time-point due to model misspecification of number of shells. Electroencephalography and Clinical Neurophysiology, 88, 1-11.

Zwick, W. R., & Velicer, W. F. (1986). Comparison of five rules for determining the number of components to retain. Psychological Bulletin, 99, 432-442.

Figure Captions

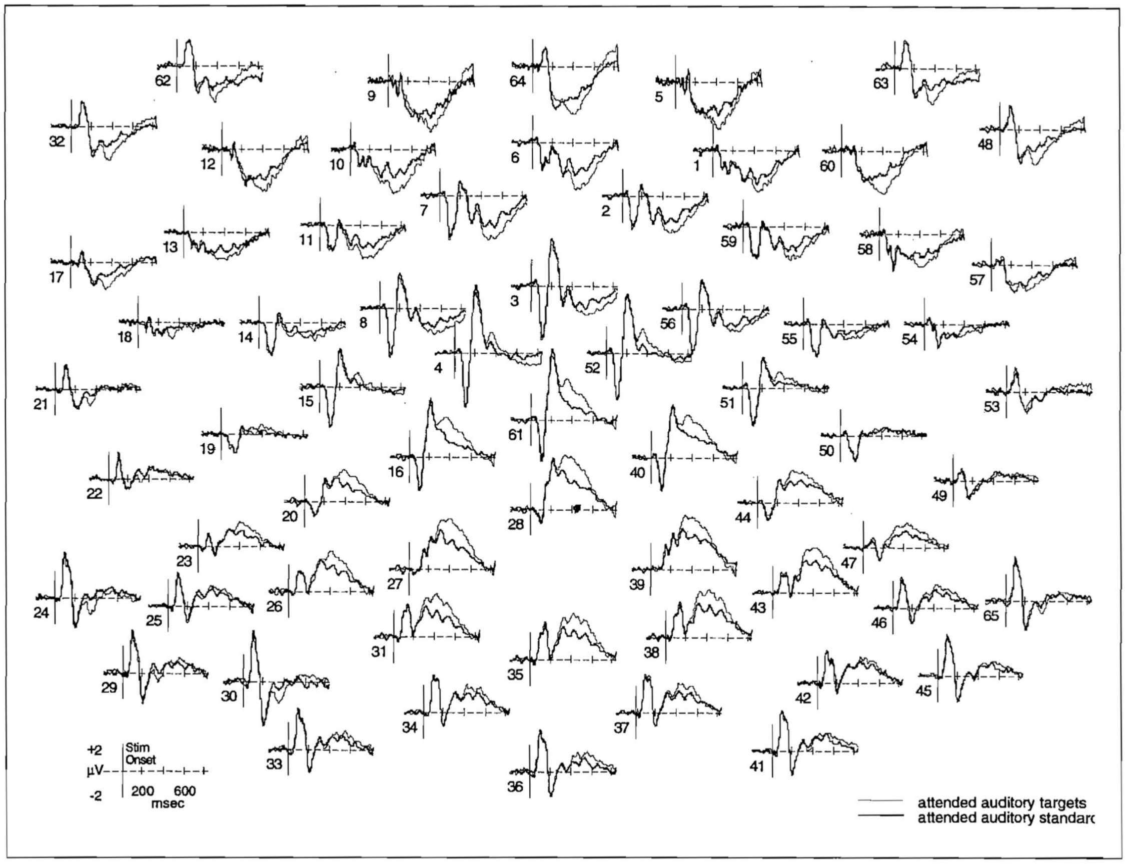

Figure 1) Grand average of attended auditory standards and targets (using average reference transform). Waveform plots are laid out roughly topographically with the top of the figure corresponding to the front of the head. Channel 65 is the reference site activity estimated by the average reference procedure. The vertical line indicates stimulus onset in each plot. Ticks on x-axis indicate 200 ms intervals. The thick line indicates standards and the thin line indicates targets.

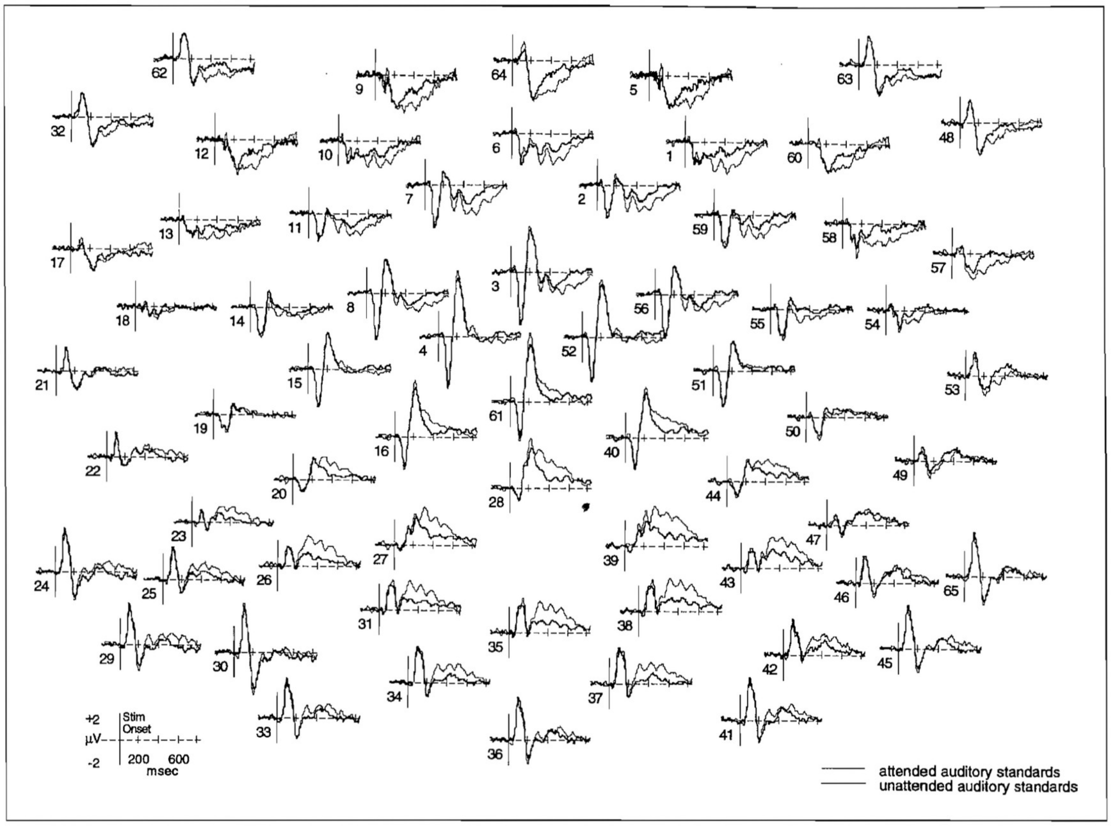

Figure 2) Grand average of attended vs. unattended auditory standards. The thick line indicates unattended standards and the thin line indicates attended standards.

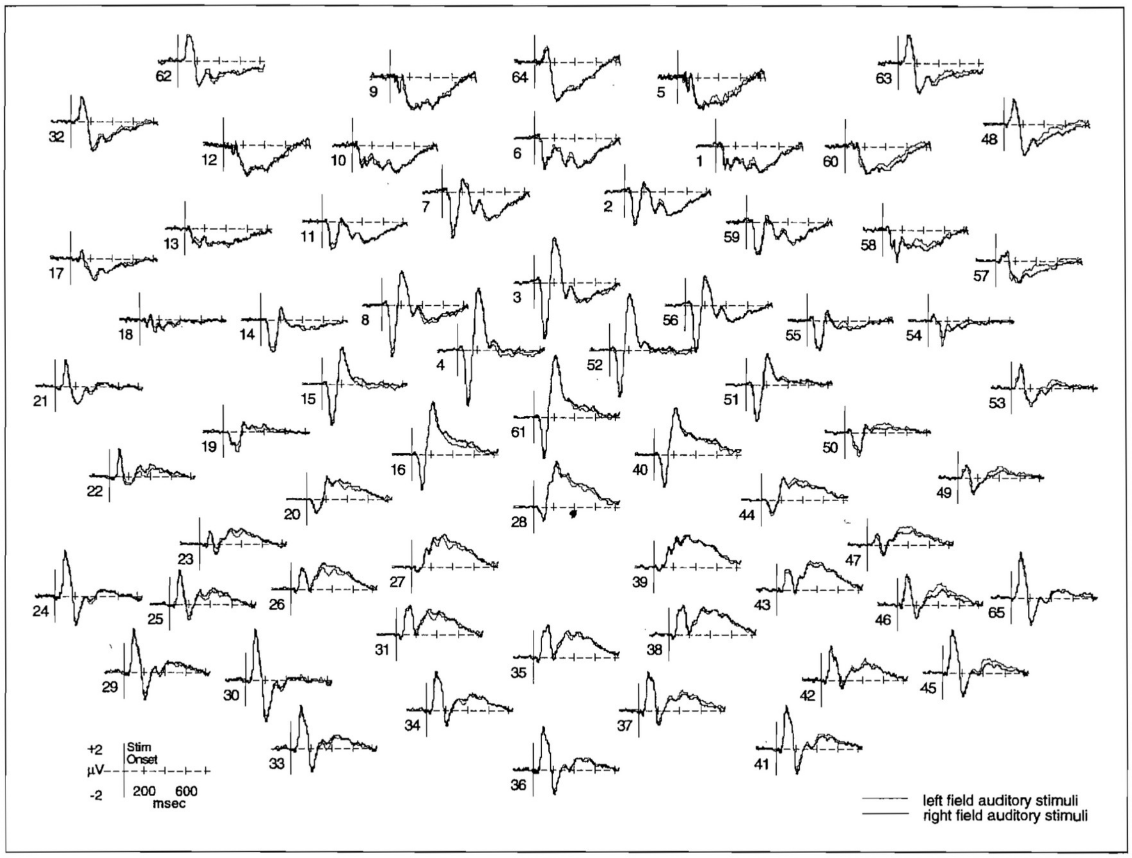

Figure 3) Grand average of left vs. right auditory stimuli. The thick line indicates right field stimuli and the thin line indicates left field stimuli.

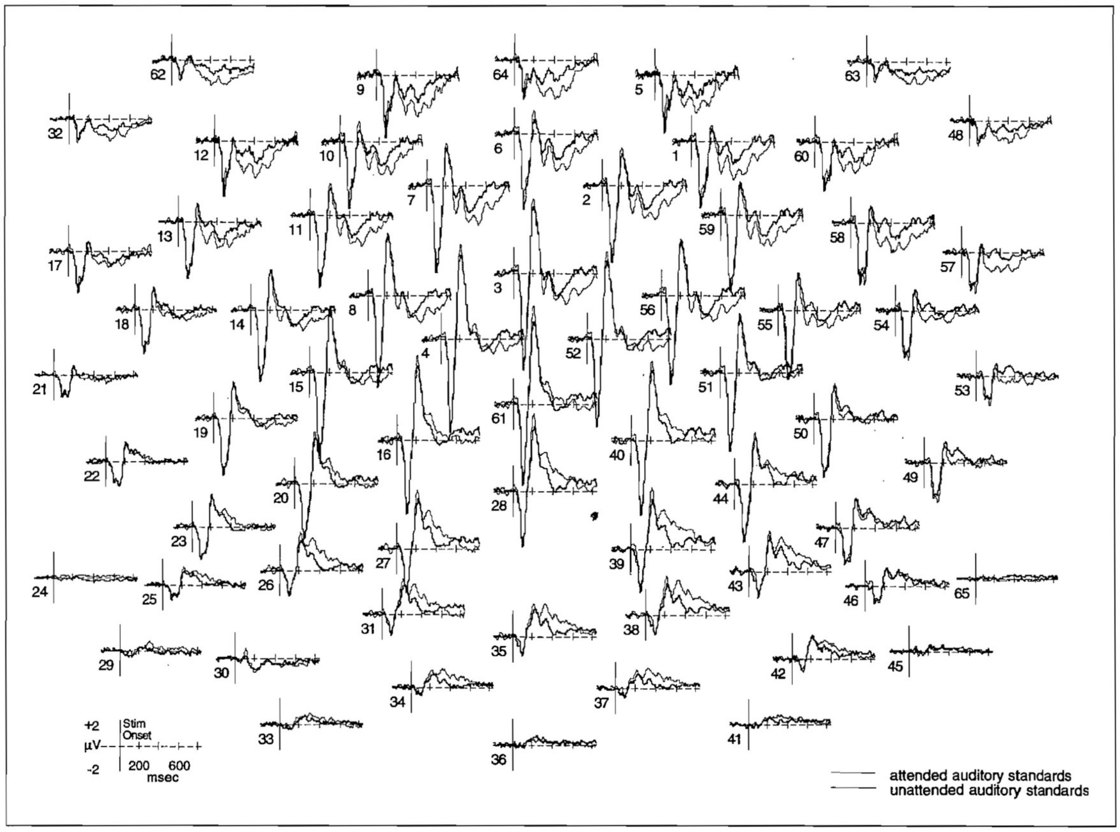

Figure 4) Grand average of attended vs. unattended auditory standards using averaged mastoids reference. The thick line indicates unattended standards and the thin line indicates attended standards. The mastoid channels (24 and 65) split the difference between the two sites.

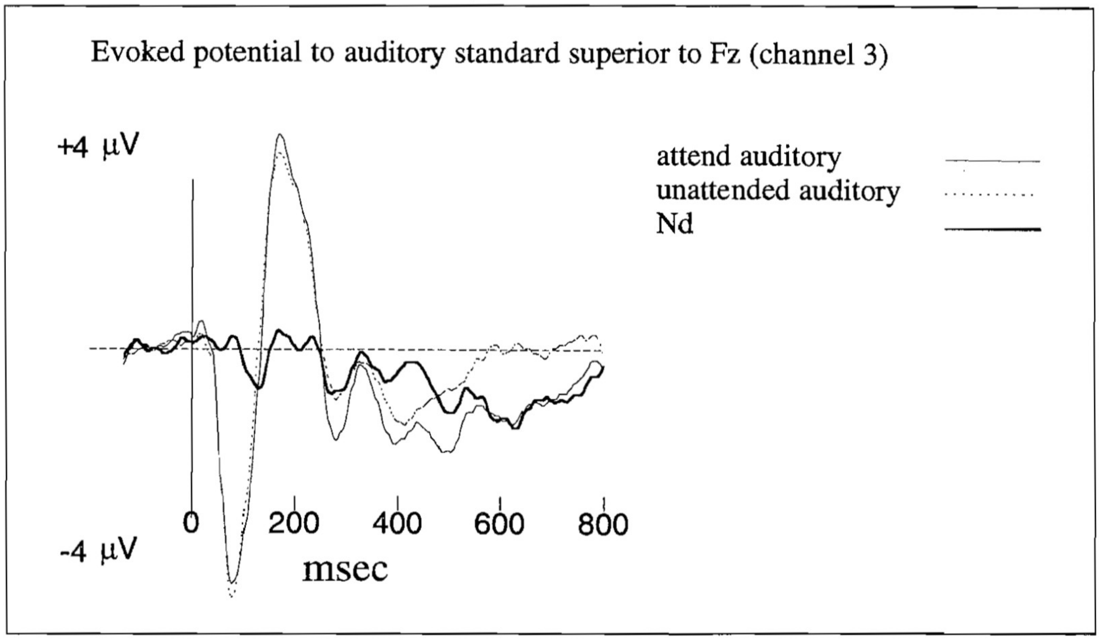
Evoked potential to auditory standard superior to Fz (channel 3)

Figure 5) Comparison of attended vs. unattended auditory standards to their difference wave near Fz.

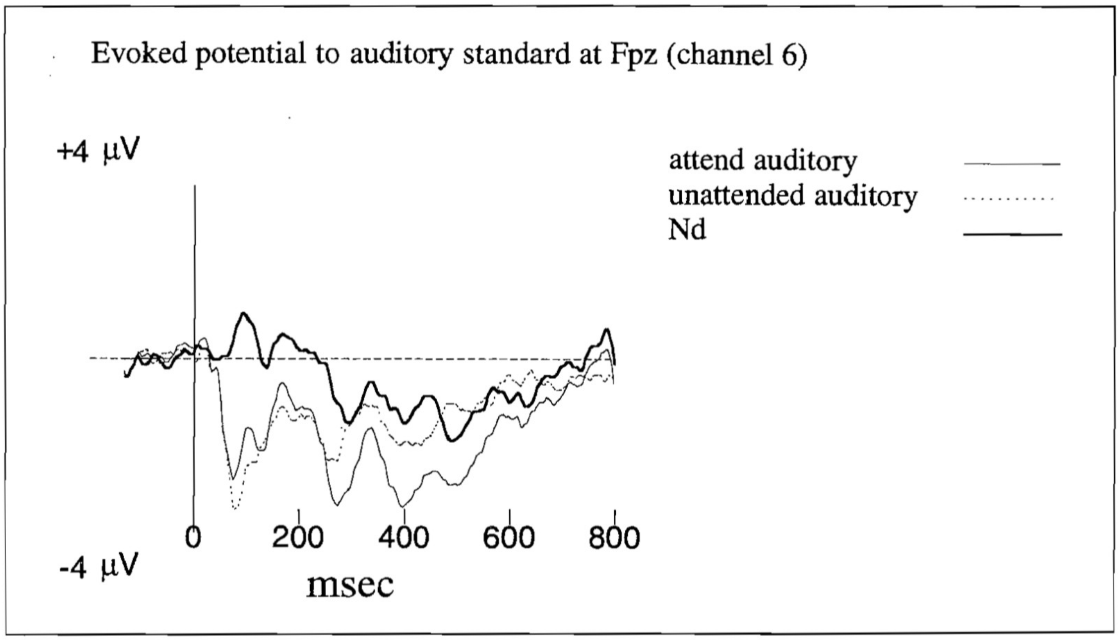

Figure 6) Comparison of attended vs. unattended auditory standards to their difference wave at Fpz.

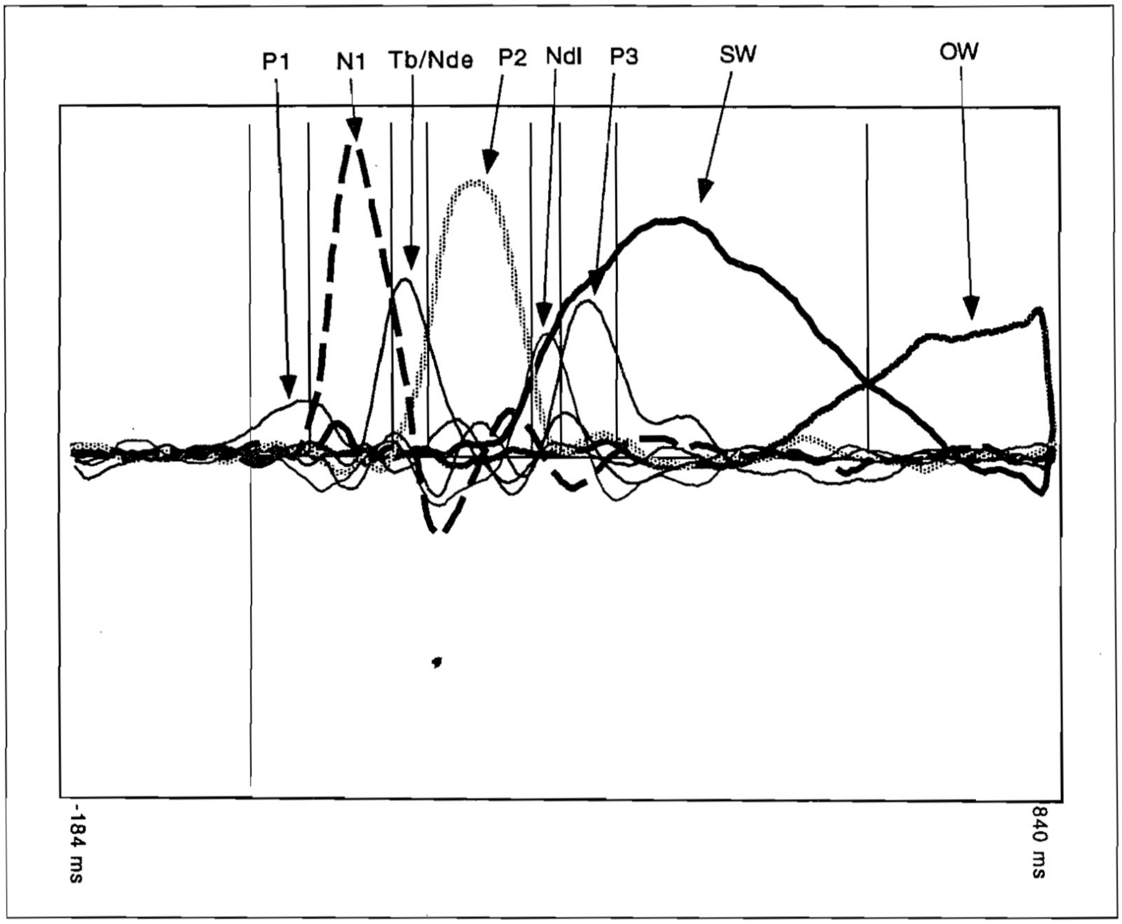

Figure 7) Overplotted factor waveforms and resulting windows. Factor waveforms are oriented so that the major deflection of each points upwards. First vertical line indicates stimulus onset. All vertical lines delimit boundaries of the ANOVA windows as defined by the factors. Each factor (and the window it defines) is labeled by the arrows.

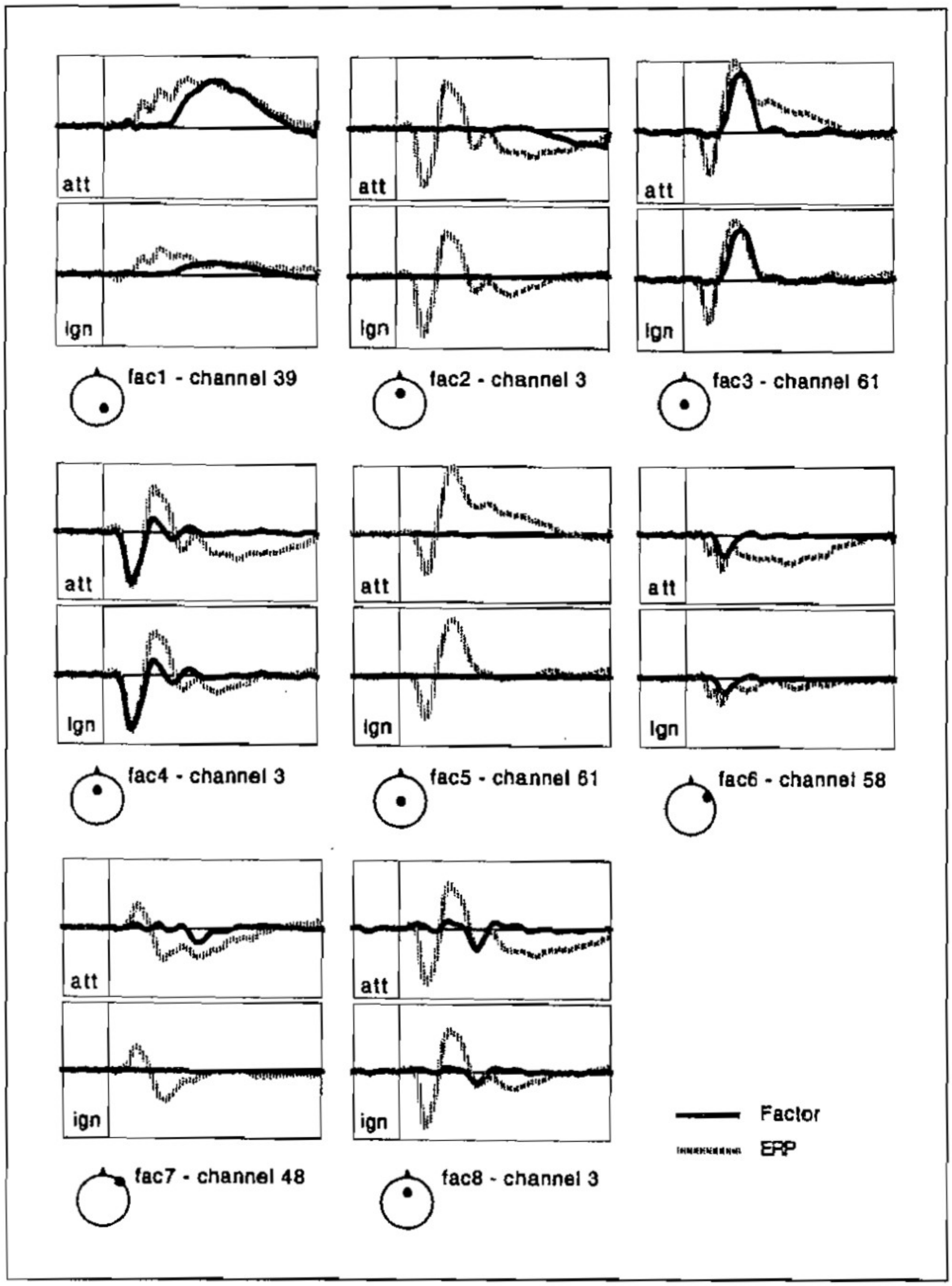

Figure 8) Overplot of grand average and factor waveforms for attended and ignored (unattended) stimuli. For each factor, site of greatest amplitude (by mean factor score) is displayed with grand average and factor waveform weighted by factor score. Since factor scores are in μv, weighted factor waveform

indicates actual portion of grand average accounted for by the factor. Head figure indicates recording site of each waveform.

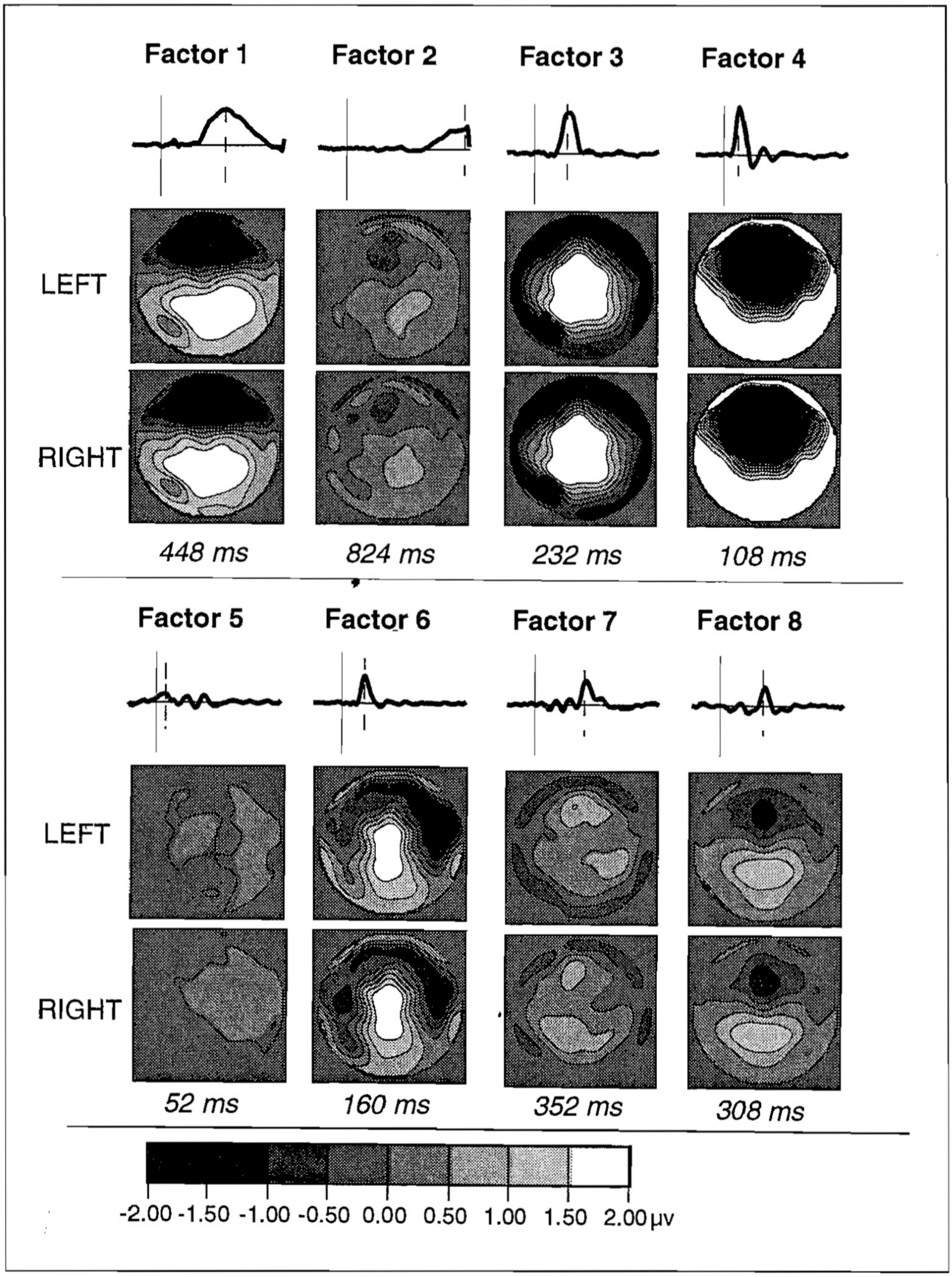

Figure 9) 2D interpolations of grand average accounted for by each factor for left and right field stimuli. White is positive and black is negative. In addition, the factor waveform (as described by the factor loadings) is presented. A dotted line indicates the time point of greatest amplitude. The 2D interpolations of the factors illustrate this moment. Note that the orientation of the factor waveforms is arbitrary since they describe the time course of both the positive and negative sides of the electrical fields.

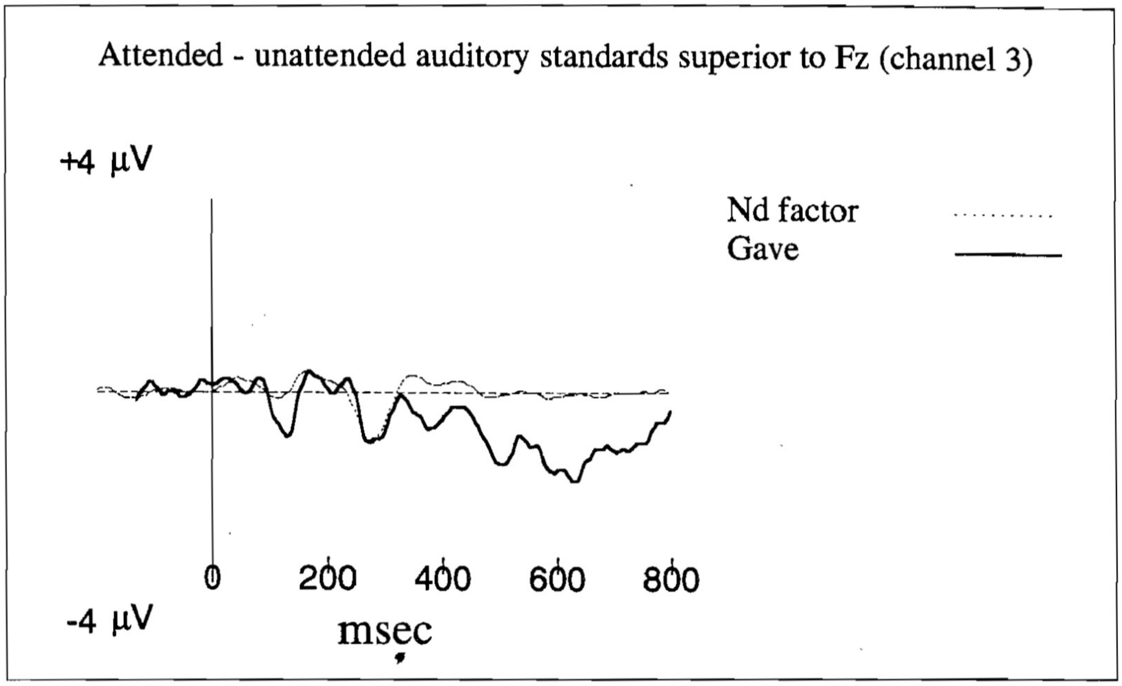

Figure 10) Comparison of Nd difference wave and Nd factor near Fz .

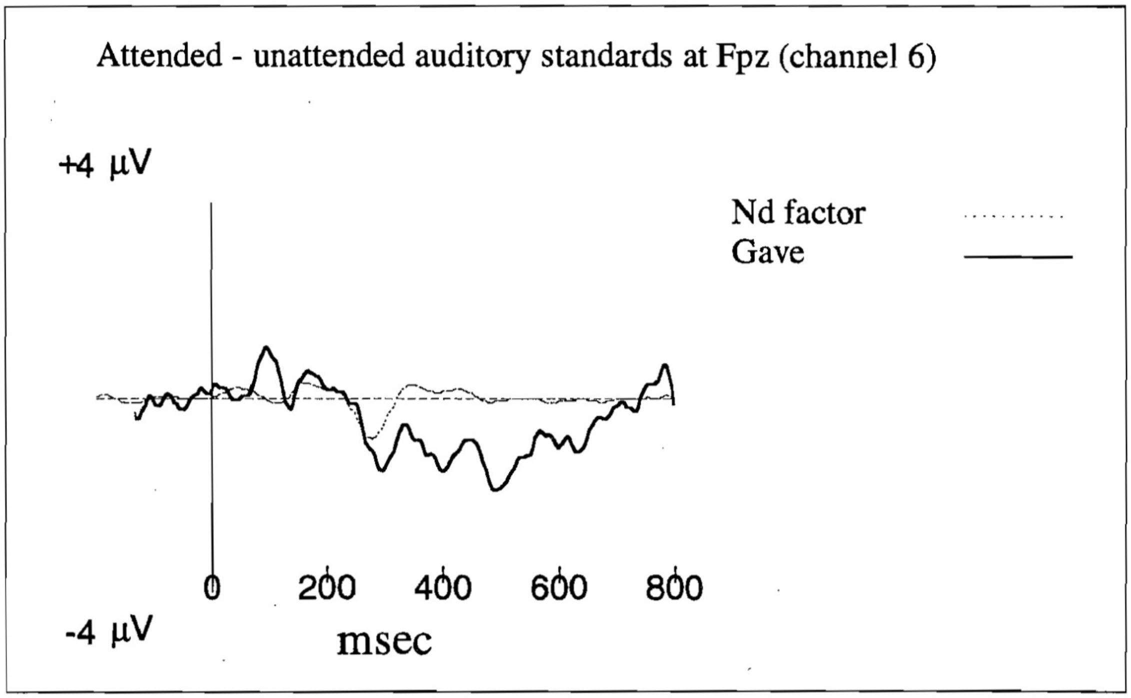

Figure 11) Comparison of Nd difference wave and Nd factor at Fpz.

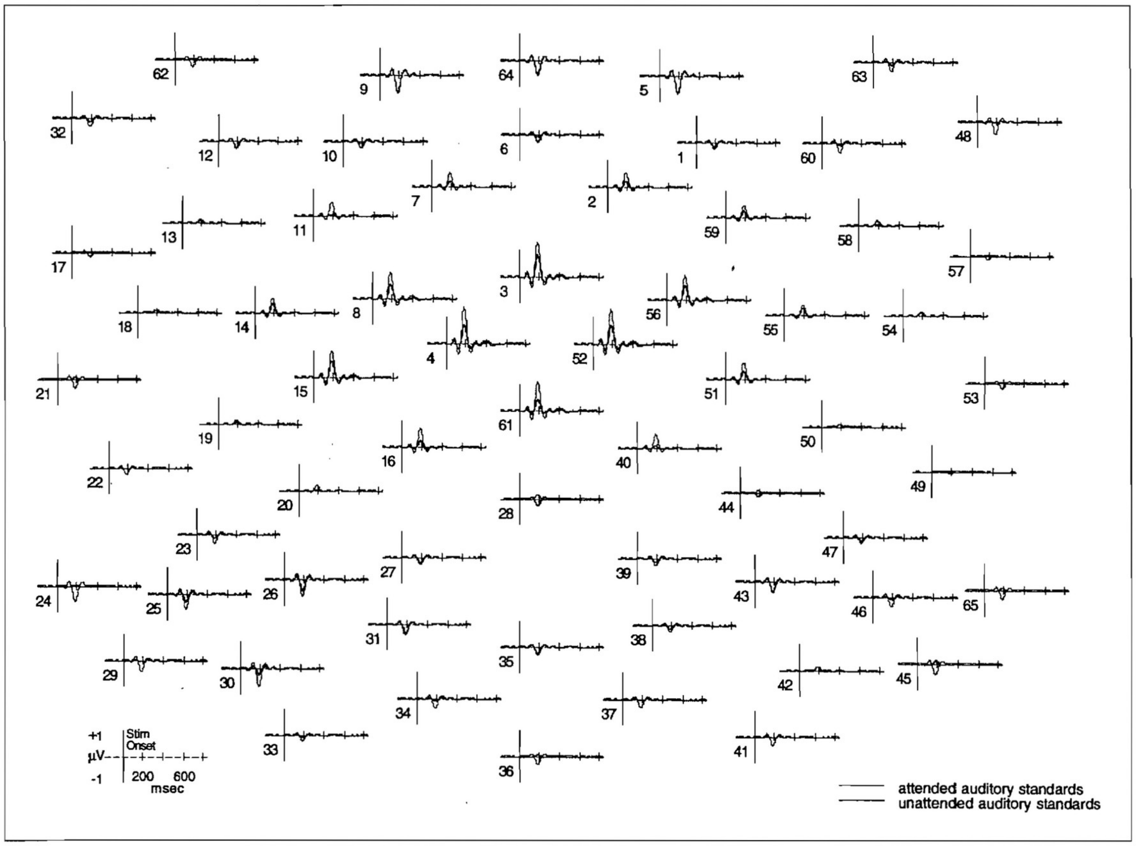

Figure 12) Portion of grand average accounted for by Nde/Pd factor. The thick line indicates unattended standards and the thin line indicates attended standards.

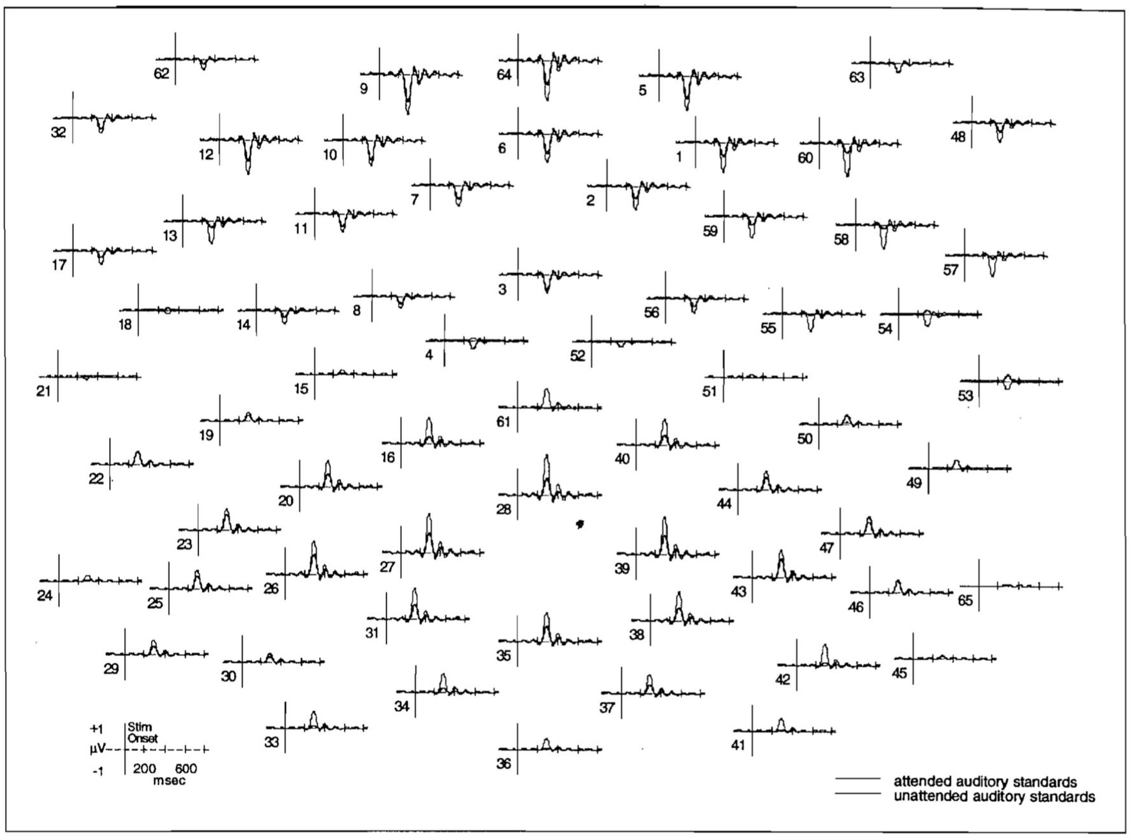

Figure 13) Portion of grand average accounted for by Ndl factor. The thick line indicates unattended standards and the thin line indicates attended standards.

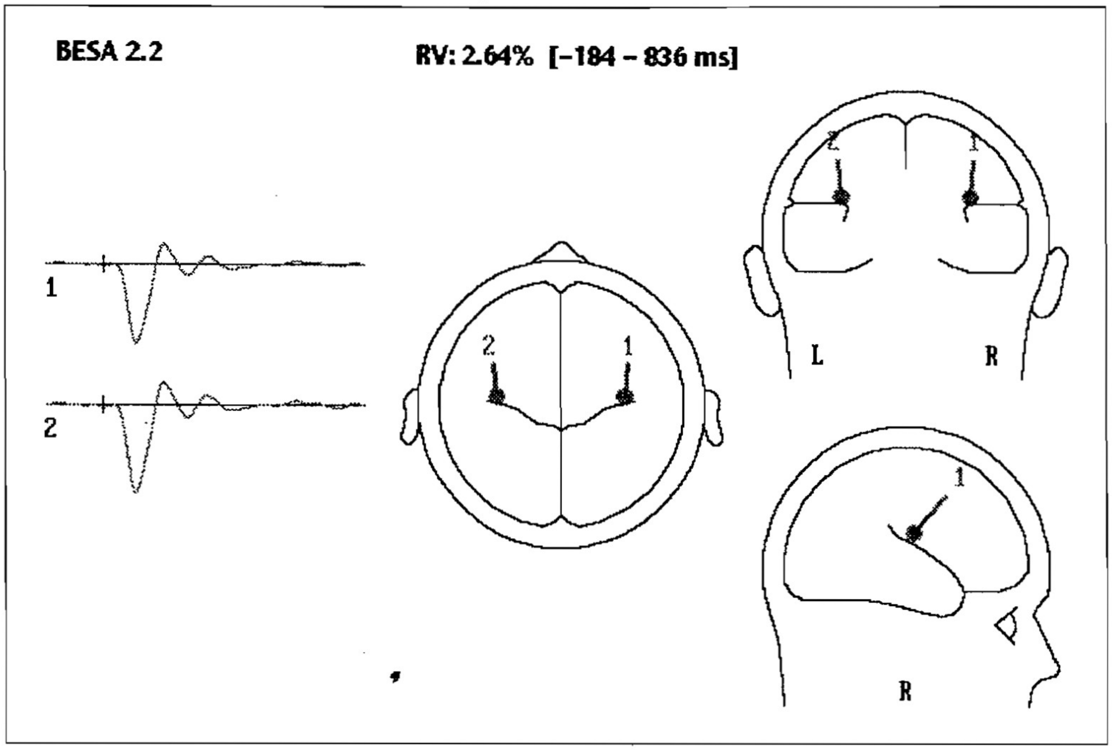

Figure 14) Dipole model of N1 factor.

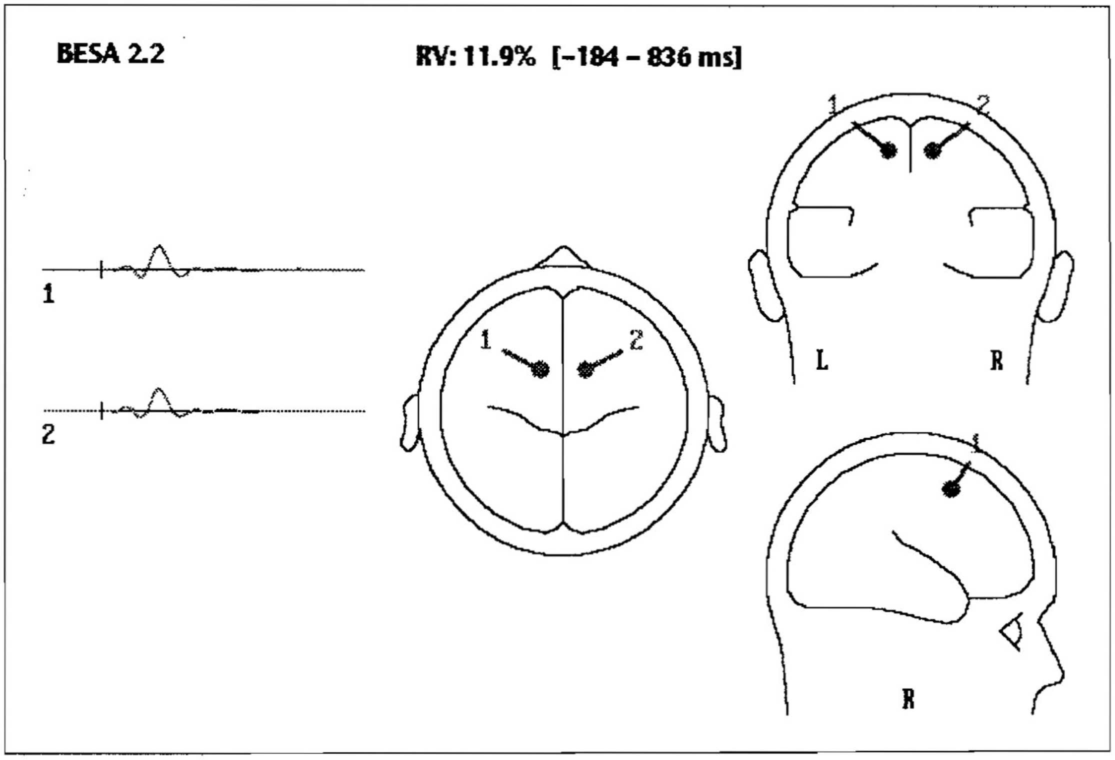

Figure 15) Dipole model of Nde/Pd factor.

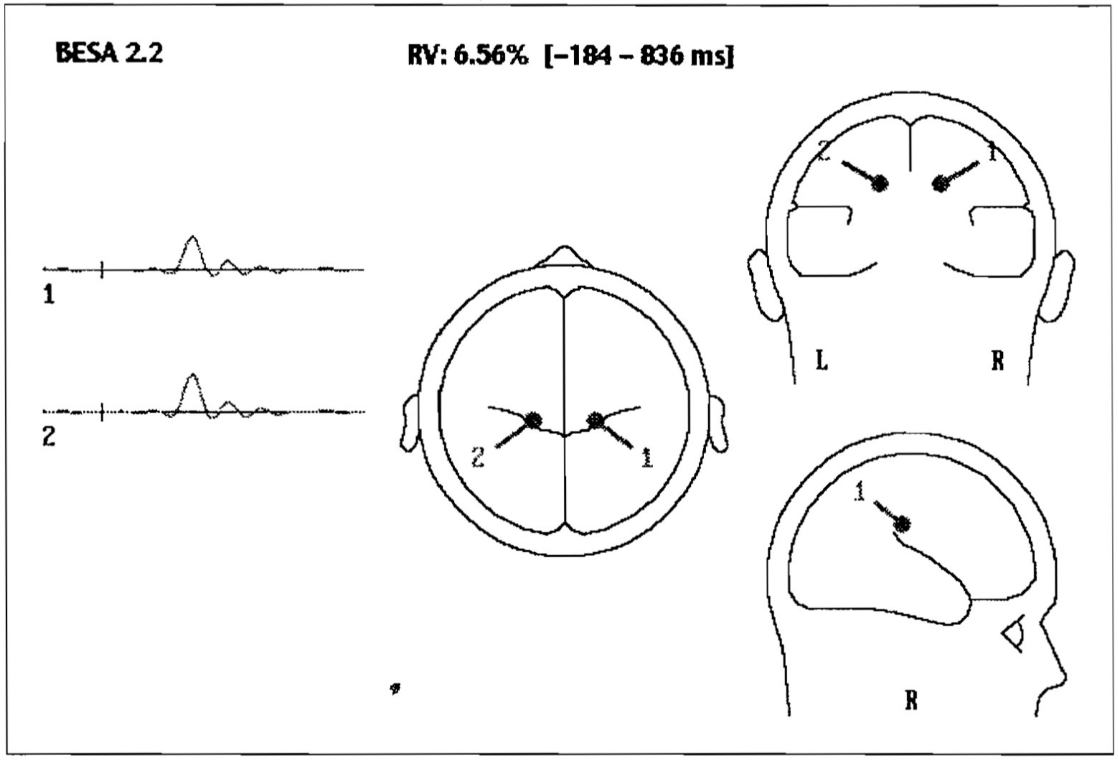

Figure 16) Dipole model of Ndl factor.

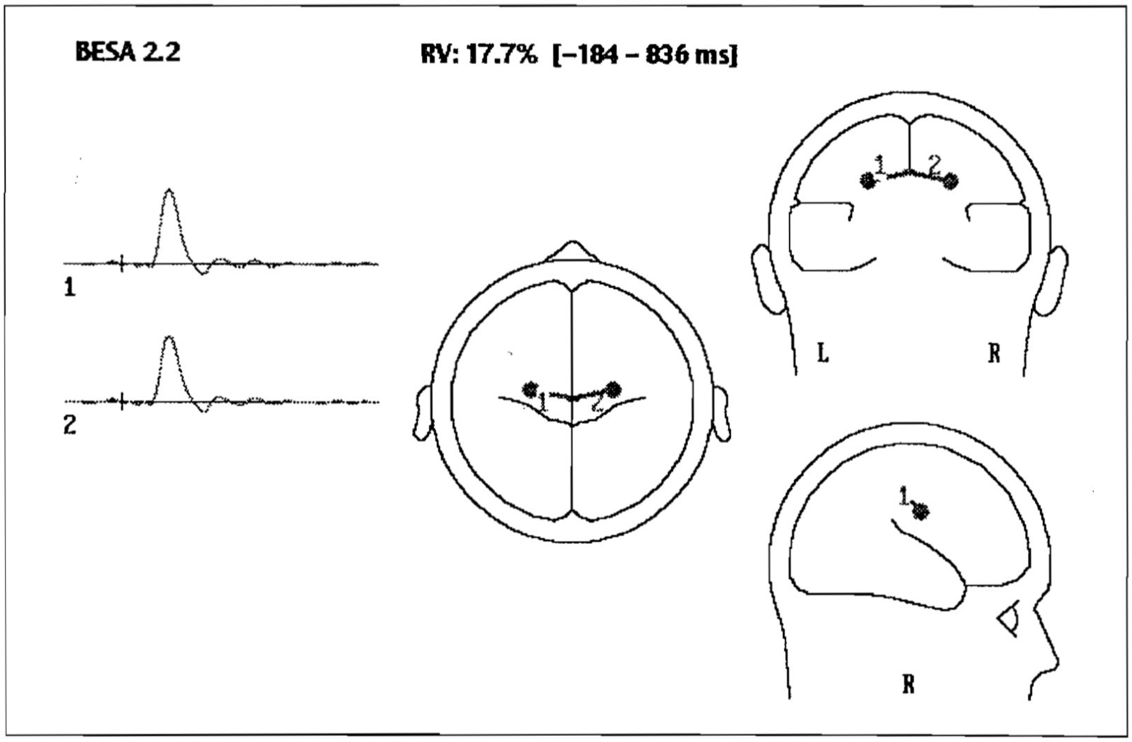

Figure 17) Dipole model of Tb factor.

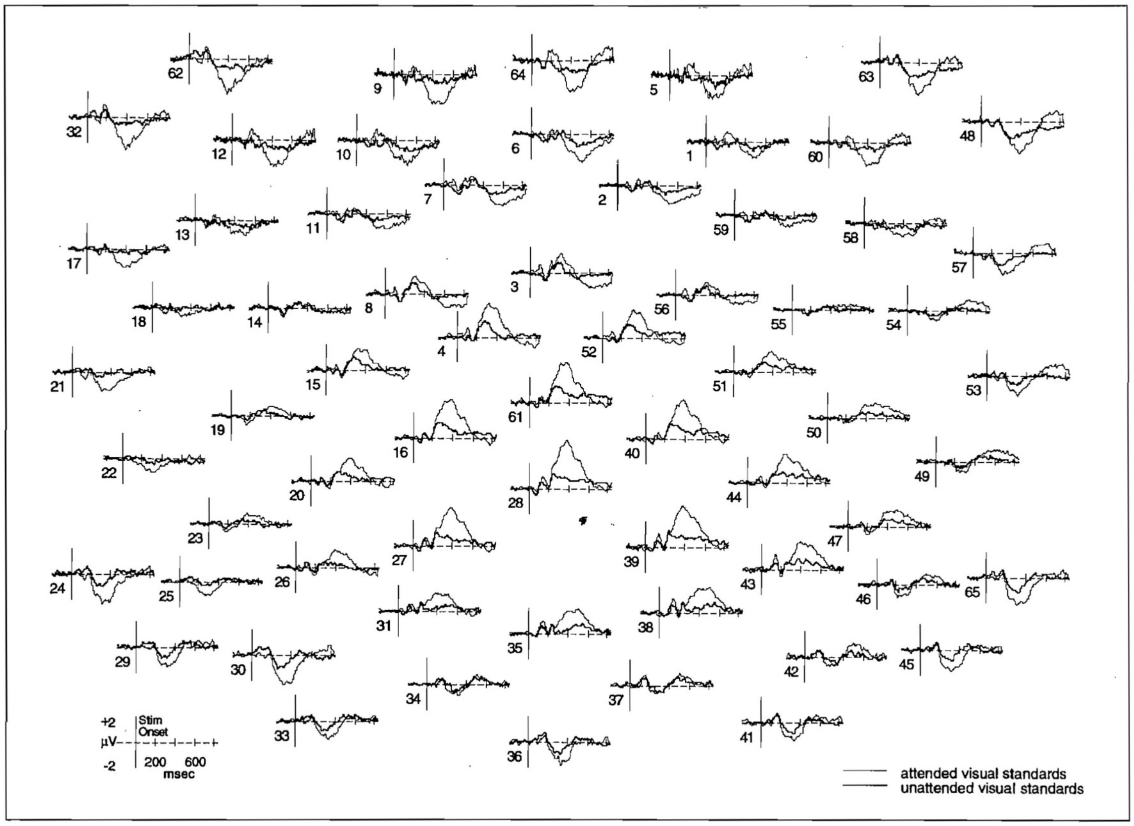

Figure 18) Grand average of the visual attention data. The thick line indicates unattended standards and the thin line indicates attended standards.

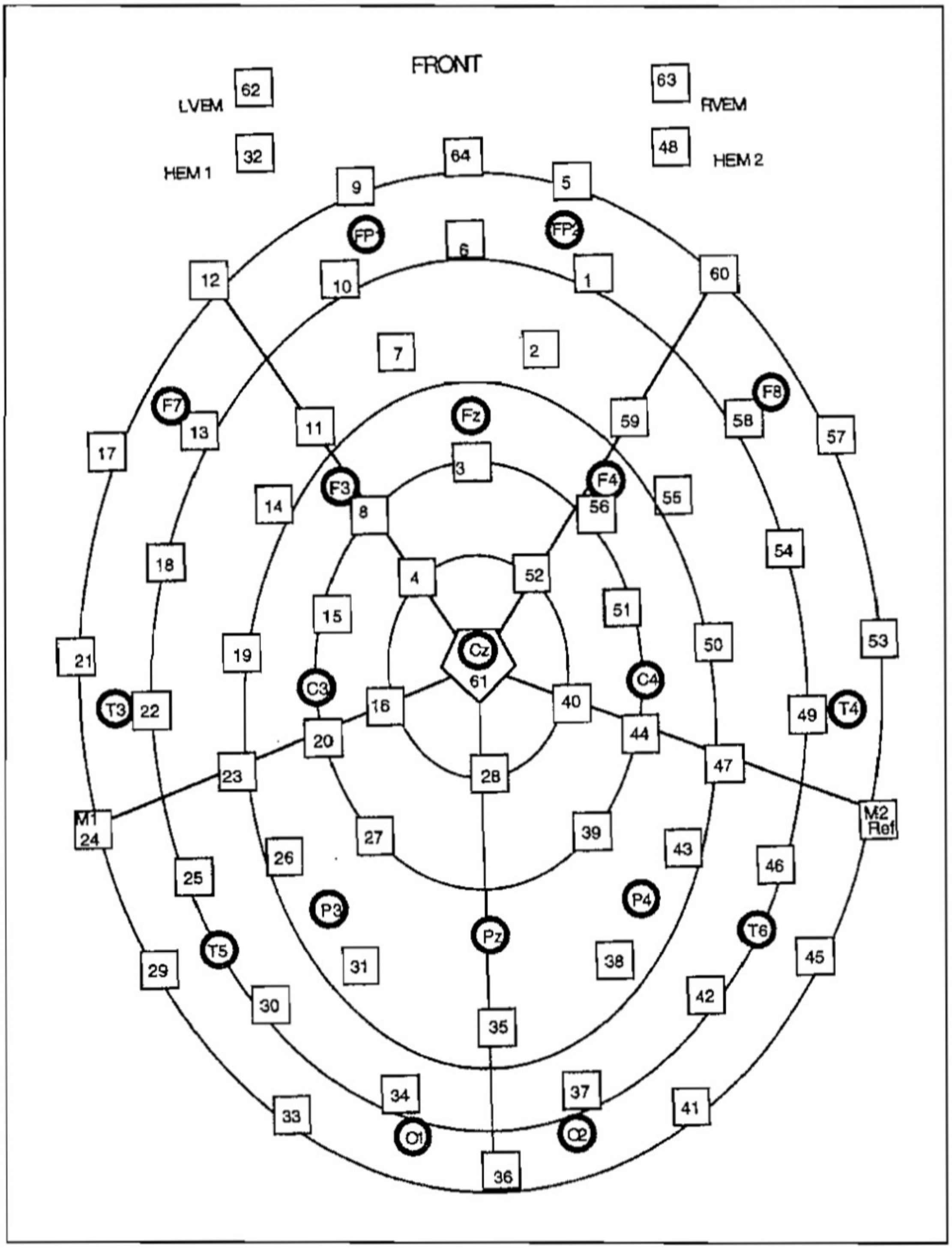

Figure 19) Location of recordings sites on the scalp, including reference site at M2. For reference sake, dark circles indicate 10-20 system sites. The front of the head is at the top of the figure. Oval lines indicate contours of the scalp.

Spatial ANOVA Factors

Site	Hemisphere	Channels
Anterior Inferior	Left	9, 12, 17, 21, 32, 62
Anterior Lateral	Left	7, 10, 11, 13, 14, 18, 19
Anterior Superior	Left	4, 8, 15
Anterior Inferior	Right	5, 48, 53, 57, 60, 63
Anterior Lateral	Right	1, 2, 50, 54, 55, 58, 59
Anterior Superior	Right	51, 52, 56
Posterior Inferior	Left	24, 29, 33
Posterior Lateral	Left	22, 23, 25, 26, 30, 31, 34
Posterior Superior	Left	16, 20, 27
Posterior Inferior	Right	41, 45, 65
Posterior Lateral	Right	37, 38, 42, 43, 46, 47, 49
Posterior Superior	Right	39, 40, 44

Table 1. Grouping of electrode sites into regions for ANOVAs.