A Cortical Potential Imaging Analysis of the P300 and Novelty P3 Components

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Abstract: The P300 and Novelty P3 are positive components of the event related brain potential (ERP) with a latency of at least 300 ms, which are manifestations of brain activity evoked by deviant events. Spencer et al. [1999, 2001] demonstrated that these are two distinct components, both of which may be elicited, with different amplitudes, by both rare and novel events. However, the locations of the intracranial sources of the components remain unknown. We describe the application of cortical potential imaging (CPI) analysis to the data described by Spencer et al. [1999]. The ERPs were recorded from 15 healthy subjects presented with auditory oddball sequences. Cortical potential maps (CPMs) were reconstructed from the scalp potential maps (SPMs) corresponding to the P300 and Novelty P3 components by deblurring the smoothing effect of the head volume conductor. The reconstructed CPMs, derived from the SPMs by means of the CPI, showed localized areas of activity distributed in both the frontal and parietal lobes; the parietal region was active throughout the period of the late positivities. The reconstructed CPMs associated with novel events showed prominent activity at the frontal lobe (Novelty P3) followed by progressively pronounced parietal lobe activity (P300), and these two components can be well separated by the CPMs. These analyses show how the CPI can be used to relate the scalp electrical recordings to the underlying brain activity. *Hum. Brain Mapping* 12:120–130, 2001. © 2001 Wiley-Liss, Inc.

Key words: cortical potential imaging; P300; Novelty P3; inverse problem; ERP; electroencephalography

INTRODUCTION

First identified by Sutton et al. [1965], the P300 is an endogenous component of the event-related potential (ERP) [Donchin, 1979] that appears as a positive deflection that is largest at centro-parietal electrodes, with a peak latency of approximately 300 ms for simple auditory stimuli. The P300 may reflect the operation of a mechanism that updates the current representation of the environment in working memory [Donchin and Coles, 1988]. The P300 has been studied

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extensively in the so-called “oddball” paradigm [Donchin et al., 1978, 1997]. In the classic version of this paradigm, the subject is presented with a sequence of events, each of which can be categorized into one of two classes. One of the classes (the “rares”) occurs with a lower probability than the other class (the “frequents”). The subject is assigned a task that cannot be performed without categorizing the stimuli and one of the two categories appears infrequently. The simplest version of the oddball paradigm presents the subject with two different tones and has the subject respond differentially to the two tones. One of the two tones is presented on a small proportion of the trials. Under such circumstances, the rare events elicit the P300 [Sutton et al., 1965; Simson et al., 1977; Donchin et al., 1978, 1997; Donchin, 1979].

Courchesne et al. [1975] introduced a variation on the oddball paradigm by inserting into the stimulus sequence an additional class of rare events that were quite distinct from the general run of stimuli in the sequence. These “novel” stimuli elicited a positive-going wave that, unlike the P300, was characterized by a frontal maximum. The relationship between the “Novelty P3” described by Courchesne and the P300 has been a matter of some controversy. Spencer et al. [1999, 2001], using a dense electrode array, examined in detail the relationship between the P300 and the Novelty P3 by applying the spatio-temporal principal component analysis (PCA) method to the scalp-recorded ERPs obtained in classic and novelty oddball sequences. Spatio-temporal PCA aids the elucidation of the ERP components underlying experimental effects by describing the ERPs in terms of their spatial and temporal variance. Spencer et al. [1999] reported that both rare targets and novel stimuli elicited a classical P300 and, independently, a Novelty P3, and suggested that these two are distinct components, consistent with studies of patients with focal cortical lesions by Knight [1984, 1996, 1997].

While scalp ERP methodology has millisecond-level temporal resolution and plays an important role in studying the underlying brain activities, its spatial resolution is limited. An important factor in these limits is the blurring effect caused by volume conduction properties of the intracranial tissues and by the effects of the meninges, the bone, and the skin [Nunez, 1995; He, 1999]. Such blurring diffuses the potential distribution over the scalp, obscuring regional cortical activity. In order to overcome this difficulty, several approaches have been explored. Cortical potential imaging (CPI) is one of such approaches aiming at overcoming the smoothing effect of the head volume conductor by taking into account the physical properties

of the passive medium between the brain electrical activity and the scalp recording electrodes. In the CPI approach, the low-pass spatial filtering effect of head volume conductor is deconvolved and the epicortical potentials are estimated from the scalp recorded potentials [Sidman et al., 1992; Srebro et al., 1993; Gevins et al., 1994; Nunez et al., 1994; He et al., 1996, 1999; Babiloni et al., 1997; He, 1998, 1999; Wang and He, 1998]. The estimated cortical potential map (CPM) provides estimates of the activity that would have been recorded had the electrodes been placed directly over the epicortical surface, which has much closer distance to the underlying cortex as compared to the scalp that has a low-conductivity insulating skull layer between itself and the epicortical surface. Thus CPMs provide useful information regarding the underlying generators of ERPs, which augments significantly the information obtained from scalp potential maps (SPMs).

In the present study, we report the results of the application of the CPI technique, previously developed by He and coworkers [He et al., 1996; Wang and He, 1998; He, 1999], to the ERP data described previously by Spencer et al. [1999]. We focus in particular on the responses to novel stimuli. The present CPI analysis of both the raw SPMs, and the “virtual electrodes” or spatial factor loading maps generated by the PCA provide a means of examining the data from another perspective. Since the blurring effect caused by the low-conductivity skull is essentially removed in the reconstructed CPMs, the CPI analysis promises to provide a further insight into the possible brain regions, which may contribute to the P300 and Novelty P3 components.

METHODS

Data acquisition

The ERP data were acquired in a previous study reported in detail by Spencer et al. [1999, 2001]. The study was approved by the Institutional Review Board of the University of Illinois at Urbana-Champaign and was compliant with the Code of Ethics of the World Medical Association (Declaration of Helsinki). All human subjects gave informed consent. In brief, 129 electrodes from 15 healthy subjects recorded scalp auditory-evoked potentials. The data were corrected for eye movements, re-referenced to an averaged mastoid reference. In each condition, 300 trials were presented with an interstimulus interval of 1 sec. The averaged signals were further digitally filtered (0–20 Hz) and baseline corrected with a baseline of

-150 to -4 ms. Subjects responded by pressing a button on a handheld box. The subjects were presented with two oddball sequences, the Classic Oddball and the Novelty Oddball. The Classic Oddball sequences consisted of rare and frequent tones ($P[\text{rare}] = 0.12$ and $P[\text{frequent}] = 0.88$). The Novelty Oddball sequences not only consisted of rare and frequent tones ($P[\text{rare}] = 0.12$ and $P[\text{frequent}] = 0.76$) but also contained unexpected complex environmental sound samples (e.g., bird songs, laughter) that served as novel events ($P[\text{novel}] = 0.12$).

Cortical potential imaging

The CPI method used in the present study was previously developed by He and coworkers [He et al., 1996; He, 1998; Wang and He, 1998]. The CPI method we used in the present study is based on a three-concentric spheres inhomogeneous head model as illustrated in Figure 1a. The radii of the brain, the skull, and the scalp (normalized) spheres were taken as 0.87, 0.92, and 1.0, respectively. The normalized conductivity of the scalp and the brain was taken as 1.0, and that of the skull as 0.0125. A hypothetical closed surface dipole layer was constructed with radius 0.8, over which 1,280 radial dipoles were uniformly distributed. The cortical potentials were estimated at 496 observation points in order to reconstruct the CPMs.

The scalp potentials $\bar{\phi}_s$ and the equivalent dipole moments $\bar{F}$ can be related by the following linear equation

$$A\bar{F} = \bar{\phi}_s \quad (1)$$

where A is the $129 \times 1,280$ transfer matrix relating the two. The dipole moment vector thus can be expressed as:

$$\bar{F} = A^+ \bar{\phi}_s \quad (2)$$

where A^+ is the pseudo-inverse of matrix A . The cortical potential $\bar{\phi}_c$ can then be calculated by the following equation:

$$\bar{\phi}_c = B\bar{F} = BA^+ \bar{\phi}_s \quad (3)$$

where B is the $496 \times 1,280$ transfer matrix relating $\bar{\phi}_c$ and $\bar{F}$.

Therefore, as illustrated in Figure 1b, the CPI method consists of two procedures: (I) the inverse estimation and (F) the forward calculation. In the inverse estimation procedure, the dipole moment distribution

Figure 1.

(a) The source-conductor model for cortical potential imaging. The head is represented by an inhomogeneous, concentric, three-sphere volume-conductor model. A closed spherical dipole layer is constructed within the brain. (b) Graphic illustration of the cortical potential imaging method (see text for details).

tribution $\bar{F}$ is inversely estimated from the scalp potential measurement $\bar{\phi}_s$ (Eq. 2). The truncated singular value decomposition (SVD) algorithm was used to handle the measurement noise and to obtain the inverse solution of the equivalent dipole moment [Sidman et al., 1992; Wang and He, 1998; He, 1999]. The use of the closed surface dipole layer as proposed by He et al. [1996] facilitates the equivalent representation of electrical sources enclosed within the layer [He et al., 1996; Wang and He, 1998]. In the forward calculation procedure, the cortical potential $\bar{\phi}_c$ is calculated from the inversely estimated dipole distribution by solving the forward problem (Eq. 3). The smoothing effect observed in the SPMs is mainly caused by the head volume conduction, especially due to the low conductivity of the skull layer. Therefore, by examining the potential distribution over the epicortical surface, which is essentially not affected by the skull layer, a higher spatial resolution can be expected from the deblurred CPM as compared with the SPM.

The CPI analysis was applied to two representations of the data acquired by Spencer et al. [1999]. The raw voltage data recorded over the scalp at specific time

points for each of the experimental conditions, labeled here the SPM, were examined by the CPI method to provide an estimate of what would have been recorded had the electrodes been placed directly on the epicortical surface. The CPMs resulting from this analysis will be examined below. However, the maps (whether SPM or CPM) for any given point in time reflect the influence of multiple ERP components [Donchin et al., 1978]. As is well known, there is considerable variability in the duration of ERP components. Thus, at any point both the CPMs and the SPMs manifest the activity of multiple components. An examination of the relationships between measures of the ERP in an ERP data set and the experimental variables should be preceded by the parsing of the ERP waveforms into its components. The spatio-temporal PCA attempts to accomplish such parsing [Spencer et al., 1999]. As a preliminary step in the present analysis, the spatial variance in the data is subjected to PCA. That is, the covariances between all pairs of electrodes are examined to reveal subsets of electrodes whose activity is highly correlated. The principal components extracted by this analysis can be represented as maps of "virtual electrodes" that display for each component its loading on each of the electrodes [Spencer et al., 1999, 2001]. These loadings are measures of the correlation between the extracted principal component and each of the 129 dimensions of the original data space. These maps can be expressed as "equivalent voltage" maps by dividing the loadings by the variance at each electrode [Dien, 1998]. Thus, the analysis yields, for each principal component, a map of equivalent voltage distributed across the scalp. Applying the CPI analysis to these equivalent voltage maps identifies the cortical manifestation of the virtual electrodes. This, in fact, is the second application of the CPI analysis described in this study. More details regarding the PCA and the CPI analysis for the virtual electrodes will be presented below.

RESULTS

Temporal ERP waveforms

For a detailed description of the waveforms obtained in the study, and for the componential analysis of the data, see Spencer et al. [1999]. By way of illustration, we present in Figure 2 examples of the grand average waveforms at the Cz and Fz electrodes elicited by the rare and novel events, respectively. The target events occurred at time point 0 with a 200-ms prestimulus period. The classical P300 is evident in all 15 subjects' ERP waveforms elicited by either rare or

Figure 2.

Representative time course of the ERP waveforms (at Cz and Fz electrodes) elicited by the (a) rare and (b) novel events. The P300 can be elicited by both events.

novel events. The peak of the P300 recorded at the vertex is $11.10 \pm 7.19 \mu\text{V}$ in amplitude with latency of $328 \pm 17 \text{ ms}$ for the rare events, and $13.22 \pm 6.34 \mu\text{V}$ in amplitude with latency of $337 \pm 33 \text{ ms}$ for the novel events. Notably, in response to the rare events, the peak of P300 recorded at the Fz electrode is smaller in amplitude although occurring about the same time as that recorded at the Cz electrode. On the other hand, in response to the novel events, the peak of P300 recorded at the Fz electrode has similar amplitude with and occurs earlier than that recorded at the vertex.

Scalp potential maps

Corresponding to Figure 2a and b, Figures 3 and 4 show examples of the SPMs in response to rare and novel events, respectively. For all 15 subjects, the rare events elicited the classical P300 component that is

Figure 3.

The scalp potential maps (SPMs) corresponding to ERPs illustrated in Figure 2a. The SPMs elicited by the rare event exhibit characteristic parietal scalp potential distribution. The sampling time points are (a) $t = 300$ ms (b) $t = 320$ ms (c) $t = 340$ ms (d) $t = 360$ ms (e) $t = 380$ ms and (f) $t = 400$ ms. Color bar units are μV .

Figure 4.

The SPMs corresponding to ERPs illustrated in Figure 2b. The scalp potential distribution elicited by the novel event showed frontal maximum at early period of the P300, and the parietal activity gradually enhanced thereafter. The sampling time points are (a) $t = 300$ ms (b) $t = 320$ ms (c) $t = 340$ ms (d) $t = 360$ ms (e) $t = 380$ ms and (f) $t = 400$ ms. Colorbar units are μV .

Figure 5.

The reconstructed cortical potential maps (CPMs) corresponding to the SPMs shown in Figure 3. Both frontal and parietal components can be seen in the CPMs. The strength of the frontal component is comparable with that of the parietal component.

The sampling time points are (a) $t = 300$ ms (b) $t = 320$ ms (c) $t = 340$ ms (d) $t = 360$ ms (e) $t = 380$ ms and (f) $t = 400$ ms. Color bar units are μV .

Figure 6.

The reconstructed CPMs corresponding to the SPMs shown in Figure 4. Both frontal and parietal components can be observed in the CPMs. The strength of the frontal component was dominant during the early period of the P300, while the parietal component

progressively enhanced thereafter. The sampling time points are (a) $t = 300$ ms (b) $t = 320$ ms (c) $t = 340$ ms (d) $t = 360$ ms (e) $t = 380$ ms, and (f) $t = 400$ ms. Color bar units are μV .

TABLE I. Deviation of the frontal peak location and parietal peak location from the vertex in response to the rare and novel events respectively

Event type	Frontal peak deviation	Parietal peak deviation
Rare event	0.36 ± 0.19 (n = 11)	0.31 ± 0.13 (n = 15)
Novel event	0.26 ± 0.11 (n = 12)	0.40 ± 0.13 (n = 12)

characterized by the consistent centro-parietal scalp potential distribution throughout the 300–600 ms interval. On the other hand, among 12 of 15 subjects, the novel events elicited a positivity that is maximal at the frontal electrodes. This frontal activity is succeeded by a more parietal positivity during the later segments of the P300 epoch. Notably, the SPMs in response to rare or novel events showed a diffused spatial distribution caused by the smearing effect of the head volume conductor. As noted by Spencer et al. [1999], the pattern displayed by the SPMs for the novel stimuli can be either a single component with a frontal distribution or the result of the additive effects of two components, the P300 and the Novelty P3.

Cortical potential maps

Figure 5 displays the reconstructed CPMs corresponding to the rare-event-elicited SPMs shown in Figure 3. Although only the parietal activity can be seen in the SPMs, the reconstructed CPMs show more localized areas of activity distributed in both frontal and parietal lobes. This result is consistent with spatial PCA described below. The frontal peak potential value was comparable to the parietal peak potential value and their ratio kept relative stable with time (Fig. 7a), ranging from 1.08 at 280 ms to 0.80 at 400 ms. Considering the spherical head model has unit radius, the deviation of the frontal peak and parietal peak from the vertex was examined (Table I). The parietal component can be observed in all 15 subjects' CPMs with peak location at 0.31 ± 0.13 behind the vertex, while 11 subjects' CPMs showed relatively weak frontal components with peak location at 0.36 ± 0.19 in front of the vertex.

Corresponding to the SPMs shown in Figure 4, the reconstructed CPMs elicited by the novel events are shown in Figure 6. Also, both frontal and parietal activities can be simultaneously seen in the CPMs, suggesting the multiplicity of underlying brain sources at the frontal and parietal lobes, corresponding to the Novelty P3 and P300 elicited by the novel stimuli. However, during the early period of the re-

sponse to novels, the frontal component was dominant in the CPMs and thus contributed to the frontally maximized scalp potential distribution. During the later period of the response to novels—although the frontal component can still be observed in the CPMs—the parietal component became stronger and stronger in the CPMs, and the ratio of the frontal peak potential over the parietal peak potential dropped down dramatically from 3.56 at 280 ms to 1.52 at 400 ms (Fig. 7b). Among 12 of 15 subjects, the reconstructed CPMs corresponding to novel stimuli during the P300 showed prominent frontal lobe activities followed by progressively enhancing parietal lobe activities. Again, the frontal and parietal components can be well separated by examining the deviation of the peak locations from the vertex (Table I). As noted by He [1999], the CPMs are estimates of electrical potentials over the epicortical surface, which represent a robust manifestation of the underlying brain electrical activity. The surrounding low-conductivity skull layer has essentially little effect on the CPMs, whereas the SPMs are known to be strongly affected by the low-conductivity skull layer [Nunez, 1995]. The cortical manifestation of the frontal and parietal activities as observed in the CPMs suggests the importance of spatial deblurring, as presently achieved by the use of the CPI procedure [He et al., 1996; He, 1998; Wang and He, 1998].

CPI analysis of the virtual electrode maps

As is true of scalp recordings, the CPMs also represent, at any point in time, the effects of multiple components at the various electrodes (although the CPMs are much more sensitive to local brain activity than the SPMs, as we observed previously). Hence, just as was true of the SPMs, no conclusions should be drawn from a visual inspection alone of the maps about the componential structure of the ERPs. It is also desirable to further analyze the cortical maps into their constituent components to test specific experimental hypotheses. We therefore applied a “spatial” PCA on the entire data set, analyzing the covariance among electrode sites, limiting the analysis in the present case to the epoch between 252 ms and 452 ms, which is the epoch identified as relevant to our interests by the temporal PCA reported by Spencer et al. [1999]. The spatial factors (SFs) are considered “virtual electrodes,” with each factor representing a characteristic topographic pattern of variance in the data set. The factor loadings measure the correlation between each electrode and the spatial factor. Thirteen factors were retained (by the screen test) and Varimax rotated. For

Figure 7.

Variation of the peak potential with time for the frontal (diamond) and parietal (square) components (left axis). The time-series of the ratio (dotted line, triangle sign) of frontal over parietal peak potential (F/P) refers to the right axis. (a) In response to rare event, the frontal peak potential was comparable with the parietal peak potential, and F/P did not vary significantly with time. (b) In response to novel event, the frontal component was dominant at earlier stage and parietal activity gradually enhanced thereafter, and F/P dropped down significantly.

the first three SFs (P300, Novelty P3, and some other anterior activity), the loadings were multiplied by the standard deviations of the variables (original electrodes) and by the largest absolute factor score (standardized) of each SF [see Dien, 1998]. The resulting maps are considered to be “equivalent voltages” as shown in Figure 8a–c. The virtual electrode maps (VEMs) represent a statement about which electrodes are highly correlated in their response to the experimental manipulations. In this sense, the virtual elec-

trodes represent ERP components as the term was defined by Donchin et al. [1978]. Clearly, both parietal P300 and frontal Novelty P3 components can be identified from the VEMs. The CPI analysis was performed on the VEMs and resulting CPMs shown in Figure 8d–f. The CPMs corresponding to the VEMs depict activities overlying the parietal lobe (Fig. 8d), consistent with the P300 component, and the frontal lobe (Fig. 8e), consistent with the Novelty P3 component.

DISCUSSION

In the present study, we have applied the CPI method to the ERPs in a data set of 15 subjects with a particular focus on the segment of the epoch during which deviant events elicit the P300 and the Novelty P3. The present investigation indicates that the CPMs obtained from CPI analysis can improve the spatial resolution and provide, from another perspective, information on possible activated brain regions that contribute to the scalp ERP observations. By virtually “removing” the low-conductivity skull layer, the reconstructed CPMs reflect what would be observed had the recording electrodes be placed directly on the epicortical surface. It has been known for a long time that the SPMs are severely smeared in the space domain by the blurring effect of the head volume conduction, especially by the insulating effect of the low-conductivity skull [Nunez, 1995; He, 1999]. Though neurosurgeons and neurophysiologists routinely practice direct cortical recordings, this method is obviously impractical for the study of cognitive processes of healthy human subjects. The present study provides, to our knowledge, the first attempt at systematically reconstructing and analyzing the CPMs corresponding to deviance related scalp ERPs, by using a cortical imaging approach [He, 1999]. The present promising results suggest the feasibility of deblurring the skull smoothing effect and “observing” the epicortical electrical responses associated with cognitive processes in the brain.

The CPI analysis leads us to relate the P300 and Novelty P3 ERP components with their associated cortical responses. By examining the SPMs, it is seen that the rare events primarily elicit the classical parietal P300. The novel events, however, elicit strong frontal Novelty P3 before the occurrence of parietal P300, which is consistent with a previous report [Mecklinger and Ullsperger, 1995]. In comparison to the SPMs, both frontal and parietal activities can be well separated from the reconstructed CPMs corresponding to either rare or novel events. The CPMs in response to rare and novel events differ mainly in the

Figure 8.

Virtual electrode maps (VEMs) and reconstructed CPMs. (a) the VEM for the first spatial factor (SF), (b) the VEM for the second SF, (c) the VEM for the third SF, (d) the CPM for the first SF, (e) the CPM for the second SF, and (f) the CPM for the third SF. Color bar units are μV .

relative amplitude of the components they elicit. For the rare events, the parietal component is strong all along the P300 interval. For the novel events, the frontal component is more dominant at the early stage of P300 interval, and the parietal activity progressively increases thereafter. The clear separation of frontal and parietal activities in the reconstructed CPMs is consistent with fMRI studies [e.g., McCarthy et al., 1997], which reported that both frontal and parietal cortex activity is elicited by deviant events in the oddball paradigm.

In accordance with studies by Knight [1984] and Mecklinger and Ullsperger [1995], Spencer et al. [1999] suggested the independence of the P300 and Novelty P3 components from their spatio-temporal PCA, which took into account all variance in both the spatial and temporal domains among all subjects examined. The present CPI analysis of the spatial patterns of variance associated with the P300 and Novelty P3

complements Spencer et al.'s spatio-temporal PCA by providing clear evidence that deviant events elicit both the P300 and Novelty P3 components, and provides additional evidence concerning the anatomical locations of the sources of these components.

Note that the CPMs obtained by the present CPI procedure are the responses of neuronal activities over the epicortical surface. In other words, the present CPI model does not fully account for cortex that lies deep within sulci and gray matter structures. This simplification represents a limitation of the present CPI approach but also offers a unique characteristic that the deblurring of the effect of the low-conductivity skull can be achieved without knowing the exact geometry of each subject.

From a technical viewpoint, the present CPI analysis represents the first systematic experimental application of the CPI method to a relatively large data set of the ERPs. Similar to most cortical imaging ap-

proaches, the CPI method used in the present study, previously developed by He and coworkers [He et al., 1996; He, 1998; Wang and He, 1998], requires regularization in the inverse computation. The present CPI analysis of SPMs over 200 ms in three experimental conditions in 15 subjects indicates the robustness of the method as applied to experimental data. Due to the inclusion of the low-conductivity skull layer in the forward head model in the present CPI method [He et al., 1996; Wang and He, 1998] as compared to Sidman's original method of using a homogeneous sphere [1992], the present CPI method provides enhanced resolution and accuracy, eliminating the distortion caused by the negligence of the skull layer. However, unlike the well-known finite element method (FEM) based on the deblurring approach developed by Gevins and coworkers [1994], the present CPI approach does not require exact geometry information, which otherwise would have to be obtained from MRI scans of each individual subject. For neurological applications the exact geometry information is sometimes preferable and even needed [Gevins et al., 1994; Babiloni et al., 1997; He et al., 1999]. In that case, either Gevins's FEM-based deblurring method [1994] or boundary element method (BEM) based deblurring methods, developed by Babiloni et al. [1997] and He et al. [1999] will have to be used in order to achieve greater accuracy in reconstructing the CPMs. For applications of testing experimental hypothesis in cognitive science like the present application, the present promising results suggest that the use of a three-sphere inhomogeneous head model is sufficient and maybe desirable. It allows elucidation of the cortical manifestation of the corresponding scalp ERPs and is practically feasible considering the large number of subjects and experiments that need to be examined in order to draw statistically meaningful conclusions. Note also that the present CPI analysis does not intend to *localize* the brain generators in the 3D space of the brain but to *image* the cortical potentials, which can be considered an equivalent source distribution over the epicortical surface, representing important information regarding the underlying brain source generators [He, 1999]. Because the epicortical surface is close to the underlying brain activity and there is no low-conductivity layer between the epicortical observation points and brain source regions, the distribution of activity observed from the CPMs facilitates elucidation of the underlying brain source generators. The distributed activity over the parietal and frontal lobes, as observed from the CPMs, suggests that the physical sources of the P300 and Novelty P3 may either be

widely distributed and synchronized activities in superficial parietal and frontal cortex.

The CPI approach provides noninvasive representation of cortical potentials, which are the reflection of the equivalent brain source distribution over the epicortical surface, without any artificial simplifying of the actual dipole source configurations (e.g., number of dipoles) [He, 1999; He et al., in press]. Similarly, the CPI approach is different than the scalp Laplacian mapping approach [Hjorth, 1975; Nunez et al., 1994; He, 1999] in that the scalp Laplacian mapping is essentially presenting a scalp distribution of the second spatial derivative of the scalp potential over the scalp, but the CPI analysis provides estimation of electrical potentials over the epicortical surface that are responses of the underlying brain electrical activity. CPI selectively removes blurring caused by the skull layer, making it easier to characterize component topographies and potentially to tell them apart. Additionally, it could theoretically facilitate PCA; as the more two scalp topographies overlap, the more difficult it is for spatial PCA to differentiate them without misallocating variance [as shown by Dien, 1998].

On one hand, the present CPI analysis provides additional evidence and further confirms the findings by Spencer et al. [1999]. By examining the SPMs, only parietal activities can be seen in response to the rare events, while the novel events elicit frontal activities alone at the early stage and parietal activities alone at the late stage of the response to novels. However, the reconstructed CPMs show well-localized areas of activities in both frontal and parietal lobes with clear separation, in response to either rare or novel events. On the other hand, because the CPI estimates the potential distribution that would have been recorded had the electrodes been placed directly over the epicortical surface, the deblurred CPMs could provide more spatial details regarding the underlying dynamic brain activities at different time instant as compared to the SPMs. Therefore, the CPI analysis provides an important insight of the characteristics of the P300 and Novelty P3 from another perspective. By combining both the PCA and the CPI techniques, a more complete picture can be drawn to further facilitate the study of ERP components.

In summary, this study provides for the first time a systematic cortical potential imaging analysis of deviance-related components of human ERP and provides additional support for the independence of the frontal (Novelty P3) and parietal (P300) ERP components elicited by deviant events. The CPI analysis of the virtual electrode maps provides evidence that the spatial patterns associated with the P300 and Novelty P3 are

closely correlated with the parietal and frontal lobes. The ability to examine cortical responses over the epicortical surface noninvasively by means of the CPI method allows further analysis of the physical sources of brain ERPs, which have been mainly analyzed over the scalp.

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