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THE ENDOGENOUS COMPONENTS OF HUMAN EVENT-RELATED POTENTIAL IN A SINGLE TRIAL EEG RECORDING.

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INTRODUCTION

Event-Related Potentials of the human brain (ERP) have been studied by a signal averaging technique. In a single trial, a brain potential recorded on the scalp is composed not only of ERP, which is time-locked to some events, but also of on-going background brain activity (EEG). Usually the EEG is large enough to obscure the ERP. Following this, an averaging computation is made using these single trial brain potentials, which are aligned with the times of the events, and then an estimated waveform of ERP is obtained. This estimate remains valid as long as the ERP dose not vary between trials, even though its amplitudes may be very small.

The ERP is accepted as a serial composition of several components, each of which is a manifestation of the synchronized activity of a population of neurons (Donchin, 1979). ERP components are generally categorized into two classes; "exogenous" and "endogenous" components (Donchin, 1979; Goff et al., 1978; Picton and Stuss, 1980; Shimokochi, 1981; a, b, c). When the same stimulus or task is repetitively given in an experimental situation, exogenous components are evoked without variance between trials, for they are intrinsic and obligatory responses of the brain to such a sensory stimulus. The estimates which are obtained by the averaging technique are valid. However, in the case of the endogenous components of ERP, (which are evoked by the psychological demands at the time, and which are related to human active information processing) we can not assume that they do not vary between trials, even though the same stimulus and trial is repeated. The reason is that some kinds of psychological or performance factors may actively or passively fluctuate between trials. For instance, when a task is given to a subject, he may well attend to the stimulus of the task in some trials, but in other trials he may not do so. Therefore, we should assume that the endogenous components, which are related to these psychological factors, vary between trials. If this assumption is true, the averaging technique can not be used to estimate these endogenous components reliably, because it is based on a "no variance" assumption. Then to study them, it becomes desirable to analyze single trial brain potentials directly.

From another point of view, we can see another fault in the averaging tech-

nique. In studies on endogenous components, the averaging of brain potentials is performed with the assumption that single trials are classified along the dimensions of prior criterion (e. g., modality of sensory stimuli) or within each level of factors that are determined by the experimenter (e. g., the probability of stimulus presentation). Consequently, if the timing of the endogenous components of ERP are varied periodically along within the dimensions of the other factors or variables (e. g., habituation to the stimulus and situation, or practice of the task), they can be cancelled out by the averaging technique. Since any situation containing a psychological task may produce such unplanned endogenous components, the averaged waveforms can not give an adequate description of the ERP in the situation (also see John et al., 1978). For this reason, an analysis of the single trial potential is better for studying the endogenous components of ERP than an analysis based on the averaging technique.

In order to analyze the ERP components in a single trial recording, the Principal Component Analysis can be used. It separates the brain potentials into a small number of basic waveforms (Principal Components). These are autocorrelated segments of the brain potentials and are extracted from the effective variances in the situation (Donchin and Heffley, 1978; John et al., 1978). We can regard principal components as ERP components which can be described precisely and quantitatively. Moreover, by measuring the component scores, we can analyze the relationships that exist between the members of the data. Therefore, in order to determine the psychological variables of the individual PC, we can utilize the component scores.

When a guessing task is given to a subject, one can easily obtain a slow positive wave in most of the single trial brain potentials which are elicited [since the amplitude is comparativety large (about 30-40μV), and the background EEG is always desynchronized (Nageishi and Shimokochi, 1980)]. Therefore, we can apply PCA to the data set of these single trial brain potentials.

By means of the averaging technique, these positive potentials have been already identified as the P300 component (Sutton et al., 1965). It is well documented that P300 is one of the most important endogenous components of ERP and that P300 is associated with the human information processing of the stimulus (Donchin, 1979; Donchin and Isreal, 1980; Prichard, 1981). In this experimental analysis attention is focused on the structure and activity of this component. It is originally reported that the amplitude of P300 (which is the largest positive peak of the averaged waveforms), is larger for an incorrectly-predicted stimulus than for a correctly-predicted stimulus, when P300 is determined (Sutton et al., 1965). However, this assumption is not entirely accepted due to the recent inconsistent experimental results of the guessing effect (see Prichard, 1981, and Sutton et

al., 1978). It is more likely that other psychological factors, such as the frequency of the stimulus presentation and the incentive values of the stimulus are more powerful determinant of the amplitude of P300 than the prediction outcomes. Since the present analysis can evaluate some effective variables of the ERP components, the present experimental analysis can be an answer to the previous dilemma.

METHOD

PROCEDURE

The subjects are 9 male students.

Binary sequences of monaural clicks (to the right or left side), are presented at a moderate intensity substantially above threshold, through a stereo-earphone (Victor STH-2). The right and left clicks are presented in a random order. A guessing trial consists of a series of a cueing flash, a guessing response by a subject and then the presentation of the right or left click. If a subject predicts that a left click is going to be presented in a given trial, he depresses one of two buttons using his right forefinger after the flash, and if he predicts a right click, he depresses the other with his right middlefinger. The interval between the flash and the click is about 3 sec. (1.5–4.5 sec.) and approximately 1 to 3 sec. between a button-press response and a click. The trials are repeated after about 15 sec. intertrial intervals (8–25 sec.). Four sets of 30 trials are presented with about a 5 min. latency between the blocks allowing the subject to rest, (see Nageishi and Shimokochi, 1980).

RECORDING

The scalp EEG is recorded by using SANEI Ag-AgCl electrodes affixed with EEG paste (SANEI Type 700) at Cz, according to the 10-20 system, and to the connections to the earlobes and the forehead are grounded. An additional pair of electrodes records the eyeblink and eye movement potentials. The EEG and EOG are amplified by the SANEI 1A52 amplifier (time constant is set at 0.3 sec. and the upper half amplitude decay at 60 Hz.) and recorded on magnetic tapes by a FM recorder (TEAC R-260) for subsequent off-line analysis.

DATA ANALYSIS

Using a micro computer system (TEAC PS-80), EEG and EOG of each trial are digitized every 0.968 msec. for approximately a 600 msec. period after the click. The trials which have EOG potentials of more than ± 80 μV are discarded immediately. The digitized EEG's are averaged using a 15 points scale, which smoothes the waveform. As a result, 40 values for the brain potentials (which are separated about 14.5 msec.) have been recorded in each trial. In order to cancel out the differences between the D.C. levels of the subjects record, the

mean amplitude of the first and second value of each available trial is calculated and becomes the zero baseline. The first trial in each block is discarded in the analysis, because we consider it to be quite different in nature from the other trials. The last trial of each block is also discarded because it can not be categorized in the addressing dimension (variable C). The brain potentials from 894 trials (from 75 to 111 trials per subject) can now be analyzed.

Using a computer system (Osaka University, ACOS-1000 SYSTEM), the data are run through PCA which is computed from the correlation matrix and the variance-covariance matrix among the brain potentials at fixed time points as the association matrixes (Donchin and Heffley, 1978). Then, the principal components (PCs), which are larger than the mean of the variance at each of the time points, are further rotated using a Varimax rotation (Kaiser, 1959). Standardized component scores (Shiba, 1972; E13, mean value $=0$, S. D. $=\pm 1.0$) are calculated for each of the brain potentials and for each PC. These component scores of each subject are averaged for each variable. They are evaluated by both the t test and by an analysis of variance of the repeated measures.

RESULTS AND DISCUSSION

THE PREDICTION-OUTCOMES

The percentage of correctly-predicted clicks for each subject is between 44% to 56% of his total predictions (mean=52%), indicating that there is no significant tendency toward making either an incorrect prediction or correct prediction.

PRINCIPAL COMPONENT ANALYSIS

In order to identify the endogenous ERP components, PCA is performed. The PCA has been adopted to many kinds of averaged ERP data and it has been shown that it is best for the ERP component analysis.

VARIMAX ROTATION

Usually extracted PCs are rotated by a varimax method, but Rösler and Manzey (1981) proposed that they should not be rotated for ERP studies. However, in the present single trial analysis we do perform the rotation on the PCs, because the component loadings of pre-rotation (Fig. 1) did not represent the features of the ERP components. Because PC2 showed a broad peak of positive loadings, it can be identified as an ERP component, but since the other PCs showed both positive and negative peaks of loadings, they can not be identified as ERP components.

MATRIX

Most of the PCA applications use a correlation matrix, but in the case of the ERP data, many researchers propose using the variance-covariance matrix (Donchin and Heffrey, 1978). The difference between these two matrixes is whether or not the data to be analyzed is standardized. Since all variables in the

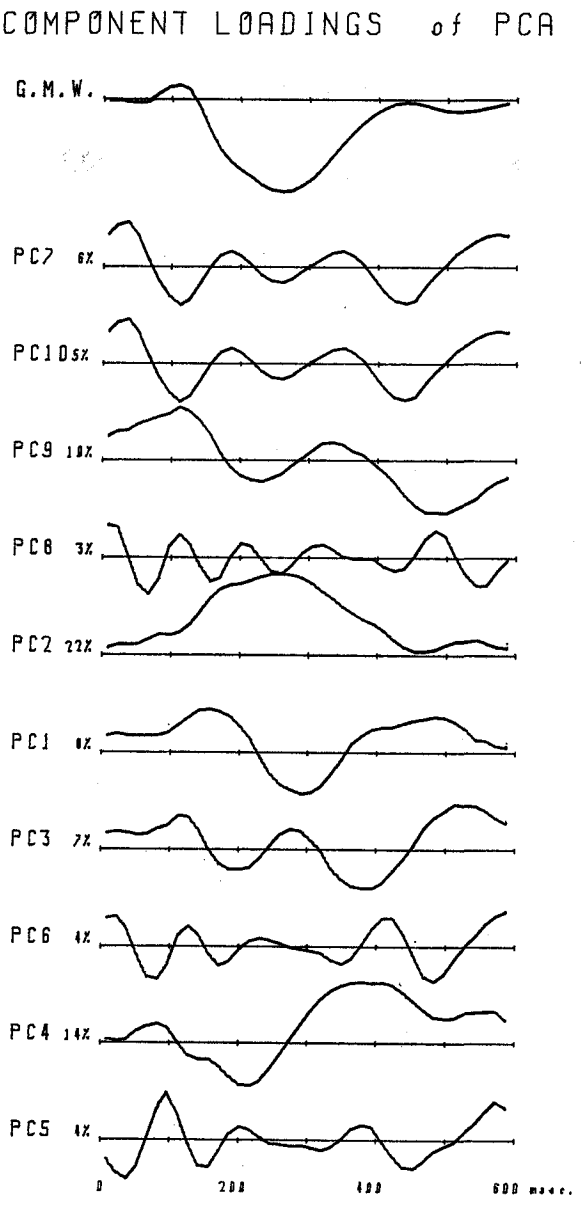

Fig. 1 Pre-rotation component loadings of the 10 PCs which are extracted by the PCA for single trial brain potentials (n=894). They are computed from the variance-covariance matrix. The numbers of percent show accounted variances of the individual PC, and the numbers of the PCs refers to the after-rotated component loadings. At the top grand mean waveform is shown.

ERP data have amplitudes at each time points, standardization is not necessary. However, the present data involve the potentials of both the exogenous and endo-

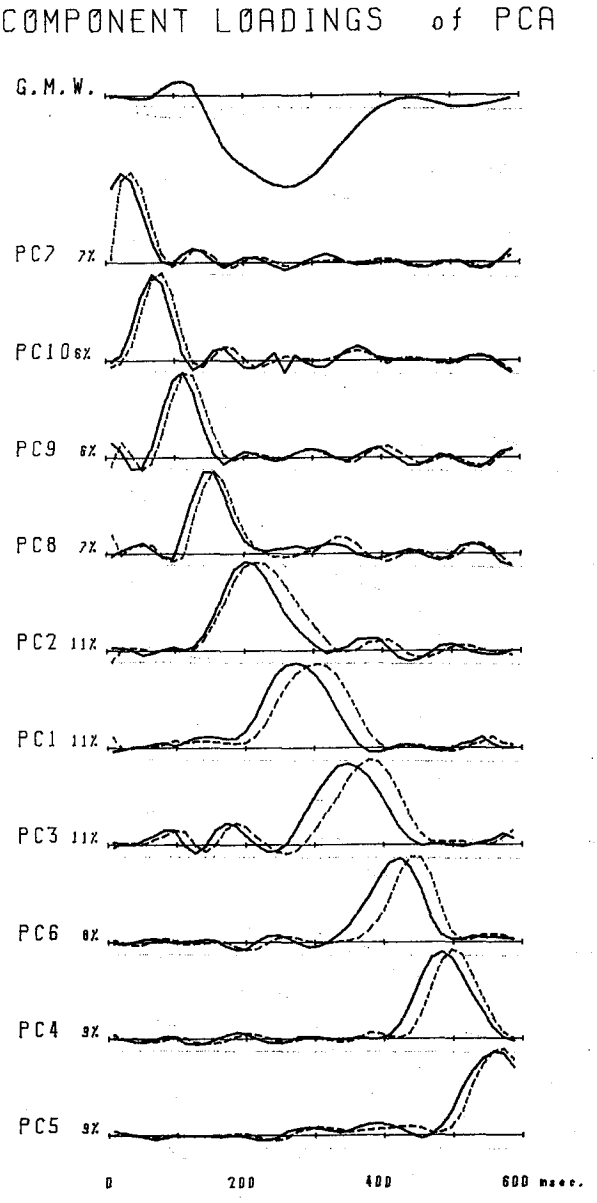

Fig. 2 After-rotated component loadings of the 10 PCs which are extracted by the PCA for single trial brain potentials (n=894). The solid lines represent the component loadings from the variance-covariance matrix and the dotted lines represent the component loadings from the correlation matrix. The numbers of percent show accounted variances of the individual PC from the former matrix. At the top grand mean waveform is shown.

genous ERP compononts. These two components have an entirely different variance; the exogenous components do not vary while the endogenous components do

vary across trials. In other words, two potentials are essentially different each other in degree and in their properties of variance. Therefore, we can compare the PCA resolutions of the correlation matrix and the variance-covariance matrix. Ten PCs can be extracted and the component loadings are essentially not different (see Fig. 2). The PCA from the variance-covariance matrix and its resolution is described in the following section.

COMPONENT LOADINGS

The solid lines in Fig. 2 represent the rotated component loadings of the PCs which are extracted by the PCA of the variance-covariance matrix. They can account for about 84% of the total variance. The number of the PCs (10) is rather large, and the variance which is accounted for by one of the PCs is rather small (11.3-5.9%). These features of the extracted PCs can be interpreted in conjunction with the homogeneity of data (Yanai, 1974). In this experiment all of the single trial brain potentials are elicited by the same task-relevant stimuli (the guessed clicks), and they are recorded at the same location (Cz), and most of them involve a large positive wave. The maximum component loadings of an individual PC are well restricted within a narrow latency-range, and they do not overlap the other PCs. Therefore, we can order these PCs in a sequence by the latency of their maximum loadings. As shown in Fig. 2, they show a clear serial composition.

STRUCTURAL ANALYSIS

In the grand mean waveform, we can only find a few peaks that correspond to the peaks of the component loadings and their latency-times (Fig. 2). Therefore, in order to recognize the properties of these PCs and the features of the variances by which they are extracted, we averaged the single trial brain potentials in regards to the values of the component scores. For the individual PC, the four averaged waveforms are presented in Fig. 3. They are the waveforms calculated from the brain potentials component scores within the four classes ($z>+.67$, $+.67 \geqq z>0$, $0 \geqq z>-.67$, and $z \leqq -.67$). The time-locations showing maximum differences are very orderly, and they correspond totally with the time locations where the PCs loaded maximally (Fig. 3). This correspondence proves the validity of this PCA.

The peak of the component loadings of PC 9 corresponds well with the negative peak at the 110 msec. latency in the grand mean waveform (the top of Fig. 2). Consequently, we can identify PC9 as the N100 (or N1) component. This identification is strongly supported by the variations of its averaged waveforms (PC9 at Fig. 3). The component scores of PC9 increases in inverse proportion to the amplitudes of this negative peak. The variance that contributes to the PC9 is the variance in the amplitudes. Likewise we can identify PC6 as the N420 component.

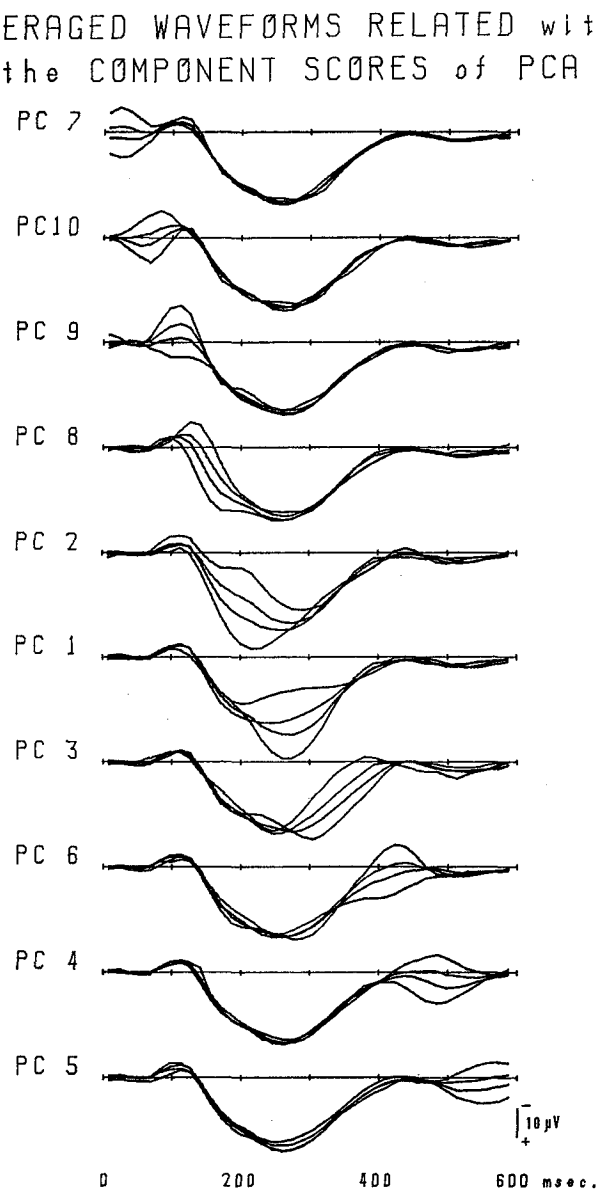

Fig. 3 Averaged waveform of the brain potentials calculated from the component scores of the PCs (PC1-PC10). At the time-location where 4 waveforms show an explicit difference, the most upper (negative) lines represent the waveforms averaged for the brain potentials that standardized component score is larger than 0.67, the middle-upper lines represent larger than 0 and less than +0.67, the middle-lower lines represent larger than −0.67 and less than 0, and the lowest (positive) lines represent less than −0.67. Single trial brain potentials are averaged within a subject and then they are averaged across the subjects with equal weight. Except for the lowest line of PC2 (n=8), they are obtained from all subject (n=9).

Within the latency range of the slow positive wave of the grand mean waveform, the four PCs (PC8, PC2, PC1 and PC3) are extracted (Fig. 2). While we can only find one positive peak in the grand mean waveform, the averaged waveforms of both PC2 and PC1 show large positive peaks at the position where their component scores are the smallest ($z \leqq -0.67$), as shown in PC2 and PC1 at Fig. 3. Therefore, it is correct that they are attributed to the variance in the amplitudes of the different positive peaks. They can be identified as P200 (or P2) and P300 (or P3), respectively.

PC8 is located at the latency range of the descending slope of the slow positive potential (Fig. 2), and the averaged waveforms of this PC (Fig. 3 PC8) do not show any distinct peaks. It is questionable whether PC8 is extracted from the variance in the latencies of the slow potential or from the variance in the amplitudes of an endogenous component which developes in this latency range. For the following reasons, we prefer the latter interpretation and PC8 is identified as an endogenous component, called tentatively, the X150 component; 1) It is an independent variance from the variances in the amplitudes of P200 and P300. 2) In the other case ($z > +.67$) the averaged waveform shows a larger negative peak at the 140 msec. latency than the N100 peak (Fig. 3 PC8). 3) It is already known that attention related negativity, which is an endogenous component of ERP, developes in these latencies (see Näätänen and Michie, 1979), and it is considered that a subject selectively attends to the clicks in some trials but not in other trials.

On the ascending slope of this slow wave, the component loadings of PC3 and the differences in its averaged waveforms are observed. Similarly to PC8, we can attribute PC3 to the variance in amplitudes of an endogenous component, tentatively called the X350 component. However, since an endogenous component in this latency range has not yet been reported, it must be examined by a functional analysis. It seems that the potential changes from 150 to 350 msec. of the latencies can be separated into four components of ERP.

Although we can only find one positive wave in the grand mean waveform around 500 msec. latency, the PC4 and PC5 could be extracted from PCA (Fig. 2). Some variables are influenced by this positive potential, and are separated into two PCs; PC4 (P500) and PC5 (P550).

The averaged waveforms related to PC10 (Fig. 3 PC10) shows both the negative and positive peaks. However, since the small positive wave in this range (about 70 msec.) is reported to be P1 from analysis of the averaged ERP (e, g., Picton et al., 1974), we can identify PC10 as this P1 component. For PC7, we can not state anything, because it is well known that in this range (below 50 msec.) the scalp potentials evoked by an auditory stimulus are concomitant with the myogenic

Table 1 Means of the Standardized Component Scores within each level of the variables.

PC	7	10	9	8	2	1	3	6	4	5
Component		P1	N100	X150	P200	P300	X350	N420	P500	P550
active latency	0-50	50-80	95-125	125-170	170-240	240-315	315-385	385-445	445-500	(msec.) 500-580
A1	.006	−.017	−.016	−.104	−.147***	.098**	−.226***	.155**	−.038	−.079*
A2	−.009	.015	−.014	.072	.146	−.182	.208	−.230	.132	.127
B1	.055	.020	.010	−.078*	−.095***	−.008	−.054	−.039	.118***	−.031
B2	−.078	−.048	−.039	.060	.067	−.058	−.008	.010	−.056	.044
C1	−.017	.058***	.005	−.076*	.006	−.061	.007	−.052	.087	.063
C2	.012	−.091	−.043	.070	−.057	.017	−.086	.019	−.039	−.037
D1	.034	.047	.003	−.126**	.080*	−.083*	−.082	−.074	.035	−.005
D2	−.037	−.055	−.024	.055	−.096	.015	.006	.035	.039	.033
E1	−.030	−.033	.003	.070***	−.017	.008	−.049	−.022	.060	−.018
E2	.034	.025	−.038	−.139	−.022	−.078	−.011	.005	.011	.054
Interactions						BC****	AB**			
SUM	.....	C	.....	B, C, D, E	A, B, D	A, D, BC	A, AB	A	B	A

* $p < .05$
** $p < .02$
*** $p < .01$
**** $p < .001$

potentials (Goff et al., 1977; Picton et al., 1974). These components are summarized in the top rows of Table 1.

FUNCTIONAL ANALYSIS

Simple effects

For these PCs we examine the following psychological variables which can influence the between trial results for this task. The trial that induces the components of the brain-potential is indexed as Trial n.

A; correctness (A1) and incorrectness (A2) of the prediction-outcomes in Trial n (the guessing effect).

B; nonalternation (B1) and alternation (B2) of the subject's predictions from Trial n−1 to Trial n.

C; nonalternation (C1) and alternation (C2) of the subject's predictions from Trial n to Trial n+1.

D; same (D1) and different (D2) sequences of the right or left stimuli from Trial n−1 to Trial n (the sequential effect).

E; early (E1) and late (E2) trials in the experimental session. (E1 consists of the trials in block 1 and 2, while E2 consists of the trials in block 3 and 4).

Means of the standardized component scores for the five variables are presented in the middle rows of Table 1. The fourteen pairs are significantly different (t test df=8). These variables influence at least one of the PCs. As Table 1 shows, one variable (A, B, C and D) is effective on more than one PC, and one PC (PC8, PC2 and PC1) is influenced by more than one variable.

Interactions

After examining the interactions between these two variables, only two interactions were statistically significant (see the bottoms of Table 1).

The guessing effect

From these results we examine the guessing effect first. It influences P200, P300, X350, N420 and P550 (Table 1). Fig. 4 presents a comparison between the averaged waveforms based on variable A and the component loadings of these five PCs. In the figure, these five PCs correspond to the difference in their amplitudes. This indicates that these PCs are mainly produced by the guessing effect. In this figure, nearly all the parts of the ERP waveform are influenced by this variable but the direction of their differences is inverse for the latencies. At the peak of P300, the amplitudes of the averaged waveform for incorrect predictions is larger than for correct predictions, but the difference is quite small. Moreover, the potentials of the components (P200 and X350), before and after P300, become more positive for the correctly-predicted stimuli than for the incorrectly-predicted stimuli. In the grand mean waveforms (the top of Fig. 4), the amplitude of P200 is nearly as large as the peak-amplitude of P300. These two

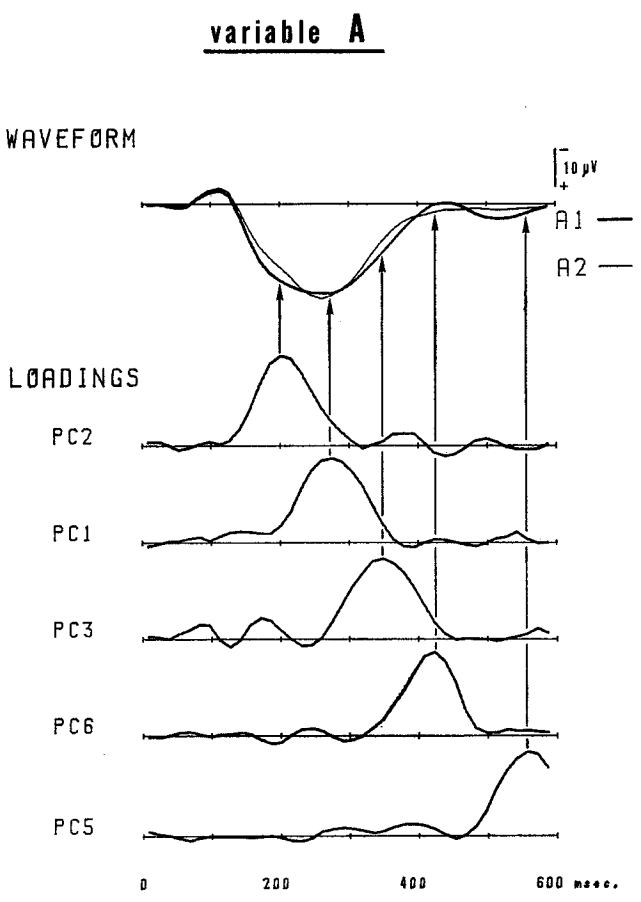

Fig. 4 The guessing effect. The grand mean waveforms related to variable A are shown at the top. In the bottom the component loadings of the PCs effective on this variable are also presented.

components somewhat overlap (see PC2 and PC1 of Fig. 3). Therefore, we do not clearly obtain the guessing effect on P300 amplitudes by means of averaging technique, because the peak amplitudes in P300 are becoming small due to the opposite polarity of P200 and X350. Sutton et al., (1978) reports that the potentials at latency 200 msec. are significantly more negative for the incorrectly-predicted stimlus than for the correctly-predicted stimulus. Consequently, the discrepant results of the guessing effect for the amplitudes of P300 (see Prichard 1981 and Sutton et al., 1978) can be interpreted by this.

The components associated with future behavior

The effect of variable C is associated with the intention of the subject. That is unexpected. The component scores of PC1 significantly interact with variable B and C ($F(1, 8) = 40.70$ $p < .001$; Table 1). As shown in Fig. 5, the amplitudes in

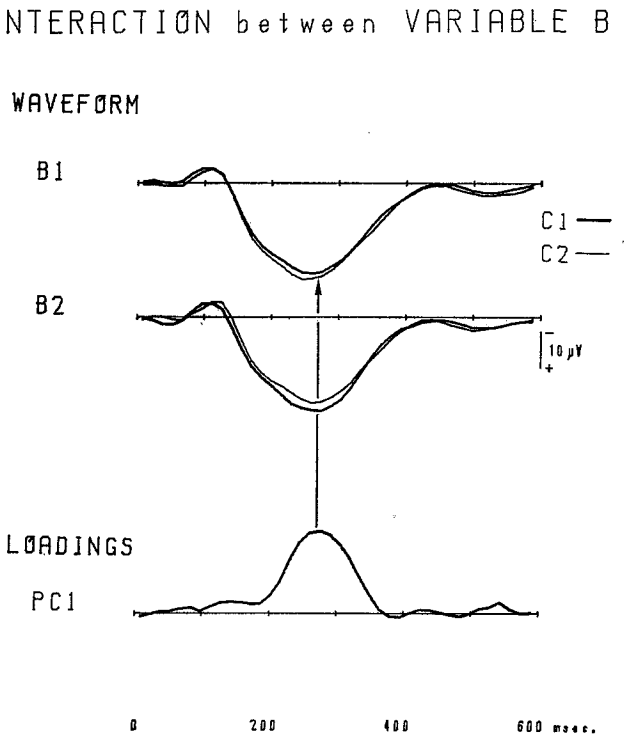

Fig. 5 Interaction of the variable B and C. The grand mean waveforms; the upper waveforms are at B1 variable and the lower waveforms are at B2 variable. The thick lines represent C1 and the thin lines represent C2. At the bottom the component loadings of PC1 are also shown.

P300 are larger when the subject alternates his prediction from the preceding trials to the present one (B2) but he does not alter the prediction for the next trial (C1). In summary, if PC1 is more positive, if X150 is more negative, and then if P300 is less positive when his prediction is alternated (at the case B2), the subjects tend to keep altering their predictions on the next trial.

It is questionable whether a common factor (e. g., motivation for the task) influences the amplitudes of these components and next predictions of a subject, or whether the large potential of these components makes a subject alternate subsequent predictions. However, this is not yet determined.

The X components

The potential in the latency of about 150 msec. categorized as X150, is more negative, if a subject alters his predictions from the preceding trial (variable B), and if he alters his predictions on the next ones (variable C), and if the stimulus is alternated from the preceding trial (variable D), and if he is not motivated to

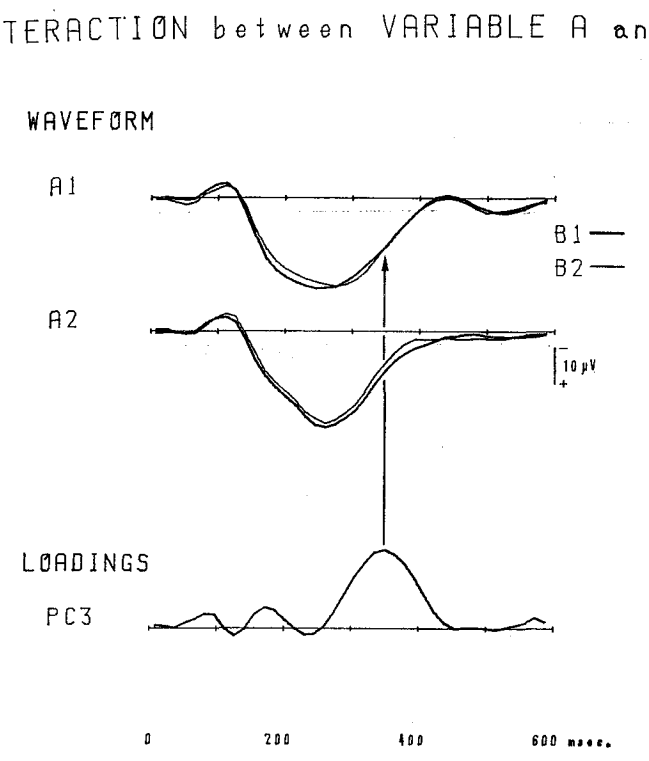

Fig. 6 Interaction of the variable A and B. The grand mean waveforms; the upper waveforms are at A1 variable and the lower waveforms are at A2 variable. The thick lines represent the waveforms of B1 and the thin lines represented the waveforms of B2. At the bottom the component loadings of PC3 are also shown.

do this task (variable E). In all of the above cases the subject attends to the stimulus, and X150 is the ERP component generally referred to as attention related negativity (Näätänen and Michie, 1979) as discussed before.

As shown in Fig. 4, the potentials of X350 are more negative when the predictions result in incorrect outcomes. The interaction between variable A and B is significant on the component scores of PC3 ($F(1, 8) = 9.19$, $p < .025$). As shown in Fig. 6, the potentials of X350 are more negative when the predictions which a subject altered his predictions from the previous trials (B2) result in an incorrect outcome (A2). Therefore, this component can be regarded as an ERP component which is associated with cognition (knowledge of the the prediction outcomes). In conclusion, both X150 and X350 are probably negative endogenous components of ERP. X150 might be an attention-response to a presented stimlus but X350 is probably a cognitive response to the prediction outcomes.

FINAL REMARKS

The last positive waves of the grand mean waveform are independently identified as P500 and P550. On the top of Fig. 4, in response to the incorrectly-predicted stimuli, the component scores of PC4 and PC5 are smaller for the correctly-predicted stimuli than for the incorrectly-predicted stimuli (variable A at Table 1), although they are not significantly different in the case of PC4. The variable in prediction-alternation from the previous trials (variable B) influences P500, but it does not influence on P550. This effect contributes mainly to the differentiation between the two components. As shown in Table 1, P200, P300, X350, N420 and P550 are all affected by the identical variable (the guessing effect). Since most of them are also affected by the other variables, they are identified as independent components of ERP (refer to Picton and Stuss, 1980). Finally, we can say that these variables and a few unknown yet present variables in this task produced these component structures of the ERP and that the differences in the effective variables contribute to the differentiations of the ERP components.

By using the PCA on the single trial brain potentials, many ERP components active in this task could be determined. In other words, portions of the potential-continuum are identified as ERP components, if they vary both autocorrelatedly and discretely between trials. Some of the identified components (X350, P500 and P550) have not yet been described using the standard averaging technique, but they are associated with some psychological factors. In conclusion, the averaging technique (which is restricted by dimensions or concerns) obscures some ERP components which are active and significant in a situation. Therefore, in order to identify describing endogenous components of ERP, the application of the PCA technique is better choice at least until the factors or variables which affect them are well understood.

SUMMARY

The purpose of the present data analysis is to find the endogenous components of human Event-Related Potential (ERP) in a single trial EEG recording and the related effective psychological variables of the components. Usually ERP components are identified by an analysis of the estimated ERP waveforms by means of the signal averaging technique, but in the present analysis it is performed by the Principal Component Analysis (PCA) of the single trial brain potentials. The reason for this PCA application is that the endogenous components which are related to the psychological functions are fluctuating autocorrelatedly and distinctly in the potential continuum (=ERP waveform) between trials.

PCA from the variance-covariance matrix is performed on the data set of 894 single trial brain potentials (n=9). This is collected during a guessing task. Ten Principal Components (PCs) are extracted and can account for about 84 percent

of the total variance. From the active latency range of the after-rotated component loadings of these PCs and the ERP waveforms (which are averaged with the single trial brain potentials with respect to their component scores) we could identify most of the PCs as the endogenous components (N100, X150, P200, P300, X350, N400, P500, and P550). We can then confirmed the utility of this method by applying PCA on the data set of the single trials. Moreover, from the analysis of their component scores, some psychological factors affecting the situation (the guessing effect, the sequential effect and the effect of the altered predictions) can be identified. In conclusion, a single ERP component is sometimes influenced by one or more factors and that a single factor is effective on one or more endogenous components, thereby indicating that these component structures of endogenous ERP components can be produced by the psychological factors which are active in the situations.

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