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REAL-TIME DETECTION OF STEADY-STATE EVOKED POTENTIALS

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In order to use the visual evoked potential as a real-time monitor of the state of the visual system, a monitoring technique was developed to maximize the signal-to-noise (S/N) ratio. System response parameters (co-power, phase angle, and coherence) are estimated for each subject from an ensemble of FFT's during a pre-testing period. These parameters are then used to calculate a weighting function which is used in real-time to perform amplitude normalization, coordinate rotation, and optimal weighting of the terms of individual FFT's. These terms, when summed, produce a simple real variable with maximal S/N and an expected value of 100 for normal vision and zero for no vision or blackout. This technique has been implemented with an FFT signal

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analyzer and a desk-top computer. Experimental results for six subjects indicate that a useable measure may be achieved. While improvements in the method are required if we are to have an effective real-time monitor for visual functioning, such improvements are not only possible, but feasible. Optimization of variables such as lead placement and stimulus timing promise the required improvement.

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SUMMARY

In order to use the visual evoked potential as a real-time monitor of the state of the visual system, a monitoring technique was developed to maximize the signal-to-noise (S/N) ratio. System response parameters (co-power, phase angle, and coherence) are estimated for each subject from an ensemble of FFT's during a pre-testing period. These parameters are then used to calculate a weighting function which is used in real-time to perform amplitude normalization, coordinate rotation, and optimal weighting of the terms of individual FFT's. These terms, when summed, produce a simple real variable with maximal S/N and an expected value of 100 for normal vision and zero for no vision or blackout. This technique has been implemented with an FFT signal analyzer and a desk-top computer. Experimental results for six subjects indicate that a useable measure may be achieved. While improvements in the method are required if we are to have an effective real-time monitor for visual functioning, such improvements are not only possible, but feasible. Optimization of variables such as lead placement and stimulus timing promise the required improvement.

INTRODUCTION

Modern high-performance aircraft can produce and sustain levels of acceleration (+Gz) greater than the pilot's physiologic tolerance limits. These limits, as a joint function of +Gz parameters and numerous protective devices and methods, are studied on human centrifuges such as the Dynamic Flight Simulator at the Naval Air Development Center.

Subjects can experience loss of consciousness (LOC) during exposure to sufficiently high +Gz acceleration. LOC is usually preceeded by visual symptoms: decreased visual sensitivity, dimming of the visual field, peripheral light loss (PLL), and central light loss, ending in complete light loss or blackout. PLL is commonly used as an end point indicator for centrifuge runs [1].

Real-time monitoring of PLL requires an active response by the subject. In contrast, the visual evoked potential (VEP) [2], which also reflects the integrity of the visual system, requires only a relatively passive task of viewing a visual stimulus.

Real-time monitoring of VEP as a measure of visual functioning on the human centrifuge must meet certain criteria, and stay within certain constraints. The most important are that the response-time to loss of vision must be less than approximately four seconds, with a low false-alarm rate and a very low probability of not detecting (and acting upon) a complete loss of vision. The method must not require extended subject preparation time, e.g., a many-electrode montage. The required computer capacity must be less than a full mini-computer and the non-real-time computation must not significantly extend the normal 1-2 minute rest periods between centrifuge runs.

The available real-time methods (e.g., [3, 4, 5]) did not seem to be directly applicable when considered in terms of these criteria and constraints. However, such methods did provide the broad strategy for attempting a solution.

To provide a continuous flow of data, we chose to utilize the steady-state VEP [3]. A monitoring method, staying within these computer capacity and time constraints, was developed [6]. This method was implemented on a desk-top computer (HP 9825T) and an FFT-based low-frequency dual channel signal analyzer (HP 3582A), and tested with six subjects under static (non-centrifuge) conditions. The results proved encouraging and potentially useful in general VEP studies [7].

METHOD

OVERVIEW

The method requires an initial parameter estimation run, relating system output (VEP & EEG) to input (stimulus). Based on an ensemble of FFT's, calculation provides co-power, cross-power, phase angle, and coherence [8]. These are used to calculate a weighting function to be applied to single FFT's in real-time, to produce a single variable which may be labeled "Percent Vision". The weighting function performs magnitude normalization, rotation of axes such that the VEP components become positive-real, and optimal weighting. When summed together, these optimally weighted components become the variable "Percent Vision". Under the restrictive assumptions of our model, this variable should have a maximal S/N, a predicted standard deviation, an expected value of 100 under conditions of normal vision, and 0 under conditions of blackout.

PARAMETER DETERMINATION

In order to determine the basic parameters of the process we collected simultaneous ensembles of input (stimulus) and output (response) FFT's from the dual channel frequency analyzer. Here we designate the input as X(f) and the output as Y(f) where Y(f) is actually VEP+EEG. The computation of the other parameters is as follows: Input auto-power spectrum

$$G_{xx}(f) = X(f) \cdot X^*(f) \tag{1}$$

output auto-power spectrum

$$G_{yy}(f) = Y(f) \cdot Y^*(f) \tag{2}$$

and cross-power spectrum

$$G_{yx}(f) = Y(f) \cdot X^*(f) \tag{3}$$

Then, using the ensemble averages, the coherence function

$$\gamma^2 = \frac{|\overline{G}_{yx}(f)|^2}{\overline{G}_{xx}(f) \cdot \overline{G}_{yy}(f)} \tag{4}$$

SIMPLIFIED PARAMETER DETERMINATION

We are concerned only in regularities in the data, not with veridicality. In real-time, we want to process a raw FFT to produce a single optimized variable. At the level of the FFT, this means that we do not want corrections for phase-shift and pass-band ripple produced by the anti-aliasing and decimation filters in the signal analyzer. Similarly we used a uniform window function for the time function measurement.

By careful design and control of the stimulus, a number of advantages and simplifications occur. For the VEP, using a strobe light driven by a pulse train or trains, each response, whether fundamental or harmonic, is an integral multiple of the stimulus fundamental, which is chosen to be an integer multiple of the bin spacing. This eliminates "picket-fence" effects and places the response at specific harmonically related spectral points.

The stimulus and measurement processes are slaved such that each stimulus time-frame is identical

$$[x_i\,(t)]_j = [x_i\,(t)]_{j+1}$$

Since the stimulus is thus constant, then for our relativistic approach in the detection process we define the input amplitude spectrum as uniform and unity magnitude with zero phase angle over the band of interest. This eliminates the need to calculate the FFT for the input and greatly simplifies the calculations required later on. Thus

$$X(f) = 1 \tag{5}$$

and therefore

$$G_{xx}\,(f) = 1. \tag{6}$$

Then, by substituting into equation (3):

$$G_{yx}\,(f) = Y(f) \tag{7}$$

and, finally

$$\gamma^2 = |\overline{Y}(f)|^2/\overline{G}_{yy}\,(f). \tag{8}$$

Also, note that $\overline{Y}(f)$ directly specifies the phase angle of the response.

Since a response will be obtained at the fundamental and possibly harmonic frequencies of the stimulus X(f), the FFT need only be processed at those frequencies. Thus, in our application, with a 0.8 Hz spacing of a 128 point FFT over the 0-100 Hz band, using a mixed pulse train of stimuli (12.8 and 16 Hz) synchronized with a missing fundamental of f_o = 3.2 Hz, we analyzed at every fourth non-zero point, for a total of 31 points.

To summarize, our simplified computational requirements consist of:

1) For each time frame of the ensemble, compute Y(f) and decimate to include only multiples of the missing fundamental: $Y(Nf_o)$ where N=1,..., 31. For each time-frame, compute auto-power spectrum, $G_{yy}\,(Nf_o)$.

2) Compute ensemble averages, $\overline{Y}(Nf_o)$ and $\overline{G}_{yy}\,(Nf_o)$.

3) Compute coherence,

$$\gamma^2\,(Nf_o) = |\overline{Y}(Nf_o)|^2/\overline{G}_{yy}\,(Nf_o) \tag{9}$$

Unless the number of frames in the ensemble (N_f) is quite large, coherence should be corrected for bias. Thus, setting $1/N_f$ as the threshold criterion,

If $\gamma^2\,(Nf_o) \leqslant 1/N_f$, then $\gamma_c^2 = 0$ and

if $\gamma^2\,(Nf_o) > 1/N_f$, then

$$\gamma_c^2 = \frac{\gamma^2 - 1/N_f}{1 - 1/N_f} \tag{10}$$

(All further reference to coherence assumes this correction).

CREATION OF NORMALIZED REAL VARIABLES

The corrected coherence permits us to partition the power (variance about the origin) into signal,

$$S = \gamma^2 \overline{G}_{yy} \tag{11}$$

and noise,

$$N = (1 - \gamma^2)\overline{G}_{yy} = \overline{G}_{yy} - S \tag{12}$$

components. Since the noise, which is predominantly background EEG, is phaseless, its variance (which is produced by squaring and summing two zero mean, equal variance, orthogonal, linear variables) is equal to N/2 along any arbitrary axis. That is, phase sensitive detection rejects ½ of the incoherent noise. Then, defining a new axis system where the positive real axis is aligned with and of the same sense as $\overline{Y}(Nf_o)$, the new real component can be determined by defining a rotational weight,

$$W_1 = \frac{\overline{Y}(Nf_o)}{|\overline{Y}(Nf_o)|} \tag{13}$$

and calculating the function,

$$(\mathrm{Re}\, W_1)(\mathrm{Re}\, Y) + (\mathrm{Im}\, W_1)(\mathrm{Im}\, Y). \tag{14}$$

Using the expected standard deviation about the origin we derive a normalizing weight,

$$W_2 = 1/((\gamma^2 + \tfrac{1}{2}(1-\gamma^2))\,\overline{G}_{yy})^{1/2} = 1/(\tfrac{1}{2}(1+\gamma^2)\,\overline{G}_{yy})^{1/2} \tag{15}$$

Then, these weights may be combined as,

$$W_3 = \mathrm{Re}(W_1 W_2),\ \mathrm{Im}(W_1 W_2). \tag{16}$$

We may then calculate real, positive mean, unity power variables, using single FFT's in real-time,

$$R = (\mathrm{Re}\, W_3)(\mathrm{Re}\, Y) + (\mathrm{Im}\, W_3)(\mathrm{Im}\, Y) \tag{17}$$

which have the enhanced coherence,

$$\gamma_E^2 = \frac{\gamma^2}{\gamma^2 + \tfrac{1}{2}(1-\gamma^2)} = \frac{2\gamma^2}{1+\gamma^2} \tag{18}$$

(All further use of coherence assumes γ_E^2).

By combining decimation across frequency with phase sensitive detection, we have improved overall S/N by a factor of eight. By conversion to normalized, positive mean, real variables, we are in a position to optimally weight and sum these variables for further S/N improvement.

OPTIMAL WEIGHTING

In the most general form, the variance of a weighted sum of variables involves a full variance-covariance matrix [9]. It was decided that, while multiple regression [10] and/or linear discriminant [11] models could be applied, the required computation would exceed our capacity-time constraints. If we assume that all of the structure of the covariance of the variables is due to unity correlation of signal components with each other and zero correlation of noise components with each other and with signal, then a step-wise process may be used. Here, two variables are combined, the compound is then combined with the third, the resulting compound is then combined with the fourth, and so on. Computational requirements increase as a linear function of the number of variables to be combined.

For two variables [9], setting $W_1=1$, we may solve for relative weight ($W_1=1$, $W_2=W$):

$$\sigma^2_{x_1+Wx_2} = \sigma_1^2 + W^2\sigma_2{}^2 + 2r_{12}W\sigma_1\sigma_2. \tag{19}$$

The variables which we are weighting and summing are real and each have two components with variances (powers) S_R and N_R, such that $S_R + N_R = 1$. The signal variance of the resultant compound is,

$$S_{RC} = S_{R1} + W^2 S_{R2} + 2W(S_{R1}S_{R2})^{1/2} \tag{20}$$

the standard deviation is,

$$S^{1/2}_{RC} = S^{1/2}_{R1} + WS^{1/2}_{R2} \tag{21}$$

and the noise variance is,

$$N_{RC} = N_{R1} + W^2 N_{R2} = (1-S_{R1}) + W^2\ (1-S_{R2}). \tag{22}$$

To find the weight W producing the maximum S_{RC}/N_{RC}, we differentiate it with respect to W and set the result equal to zero,

$$\begin{aligned} 0 = {} & [(S_{R2}-1)\ (S_{R1}S_{R2})^{1/2}]\ W^2 \\ & + [S_{R2} - S_{R1}]\ W \\ & + [(1-S_{R1})\ (S_{R1}S_{R2})^{1/2}]. \end{aligned} \tag{23}$$

This quadratic equation is then solved for W.

Some rather tedious change-of-scale arithmetic is involved in getting from W as delivered by equation (23) to the actual weighting function to be used for optimization. In our application, we take the first of the compressed spectral points and set $W_1=0$ if $\gamma_1^2 < 0.15$, and arbitrarily set $W_1=\gamma_1^4$ if not. This defines values "S_{RC}"$=W_1^2\gamma_1^2$; "N_{RC}"$=W_1^2\ (1-\gamma_1^2)$; and "γ^2_{RC}"$=\gamma_1^2$. The γ^2_{RC} is passed as S_{R1} to the optimization equation along with γ_2^2 (if > 0.15) as S_{R2}. The delivered weight, W_D, which assumes that $S_1 + N_1 = 1$, is rescaled to,

$$W_2 = (S_{RC1} + N_{RC1})^{1/2}\ W_D. \tag{24}$$

W_2 is then used to produce the first genuine compound. Since signals add as standard deviations (eq. 21) and noises as variances (eq. 22),

$$S_{RC2} = (S_{RC1}^{1/2} + WS_2^{1/2})^2,$$

$$N_{RC2} = N_{RC1} + W^2(1-S_2), \text{ and}$$

$$\gamma_{RC2}^2 = S_{RC2}/(S_{RC2} + N_{RC2}).$$

This step-wise process continues until all useable points are exhausted.

Final values of S_{RC} and N_{RC} are used to rescale the entire weighting function, to produce an expected value of 100%. This weighting function is combined with the normalization and rotation weights to produce the weighting function for use in real-time runs. The final value of $1-\gamma_{RC}^2$ is used to set confidence limits for the variable "Percent Vision", which is computed and displayed in real-time.

The final γ_{RC}^2 also provides a simple figure-of-merit for evaluation of any change in experimental method. Changes in electrode placement, changes in stimulus parameters (e.g., intensity, frequency composition, spatial structure), or any other changes in method may be evaluated.

The method is presently being used to process only a single channel of information: the VEP measured at the mid-line (0_z). Separate processing for right and left hemispheres (0_1, 0_2) should provide a significant improvement, and still stay within reasonable bounds for required computing capacity/time. The algorithm would remain the same, treating the two channels as a single set.

EXAMPLE

Figure 1 shows a specimen real-time run for a subject with low predicted and obtained standard deviation [7]. Here, the stimulus was occluded for three time-frames in the latter part of the run. The dashed line in the figure shows the result of a two-point smoothing which provides a margin of protection against a false negative determination at the expense of an additional 1.6 second delay of the decision.

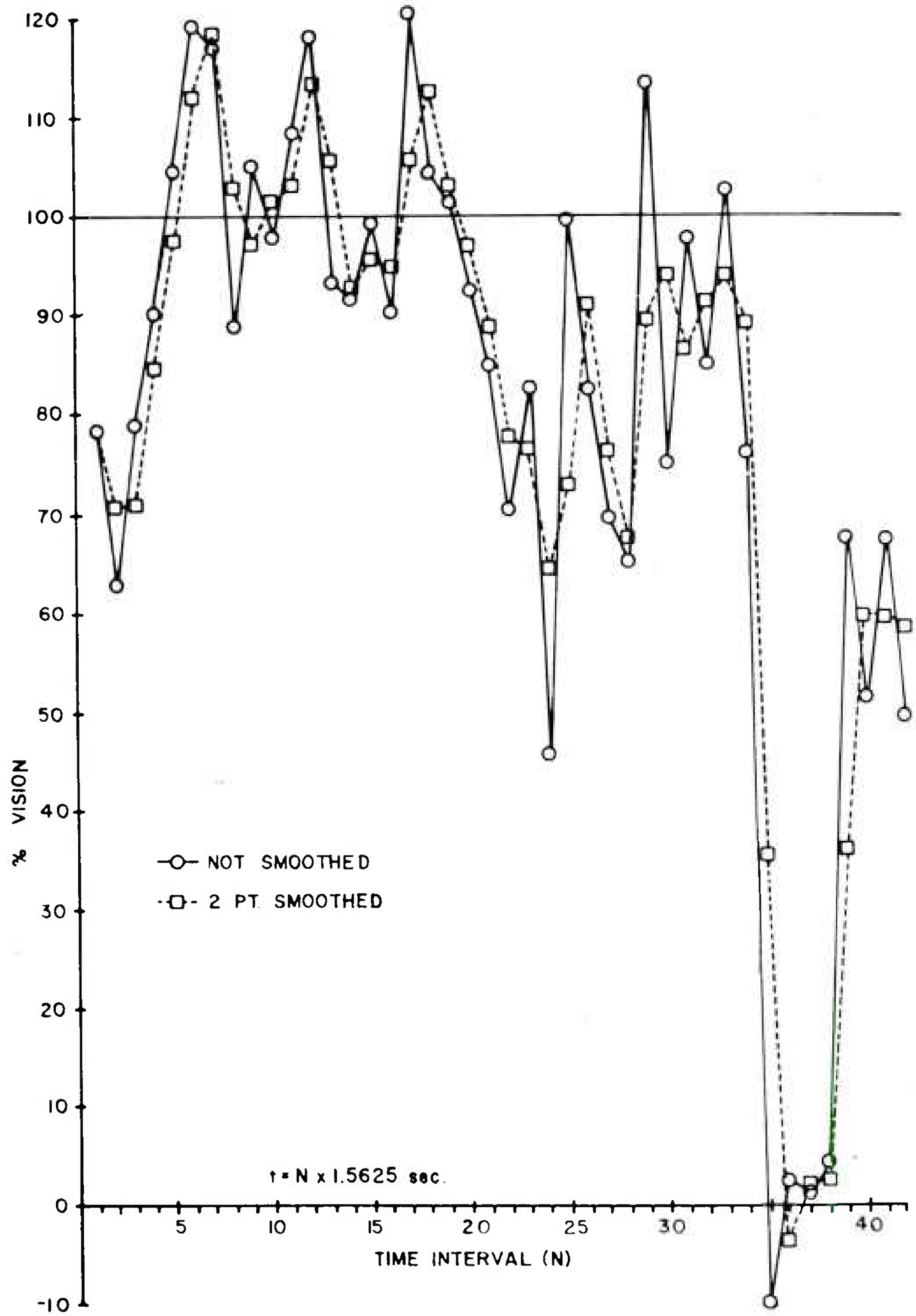

Figure 1. Specimen Real-Time Run (from [7]).

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