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Amplitude Variability of the Steady-State Visual Evoked Response (VER)

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ABSTRACT

The reliability of steady-state visual evoked responses (VER's) was determined for nine normal subjects using Fourier analyses with 1.0 and 0.25 Hz bin resolutions. No correlations were found between VER amplitudes and subjects' reports of attention, accommodation, fixation, or perceived organization of the stimulus. Across subjects, there was also no sustained amplitude modulation of the VER by any frequency (including alpha), and frequency drift of the VER did not contribute significantly to its amplitude variability. Modeling, using mixed sine waves to simulate different signal/noise (S/N) ratios, established that a significant portion of VER amplitude variability can be accounted for by noise which occurs at the same frequency as the VER and which is not removed by ensemble averaging.

Key Words: visual evoked response (VER), visual evoked potential (VEP), visual evoked cortical potential (VECP), electroencephalogram (EEG), variability index, variability, reliability, ensemble averaging, Fourier transform

The VER is a gross electrical response generated primarily by neurons in the visual cortex.[1] As such, it is a potentially valuable, noninvasive tool for objectively assessing many aspects of vision. VER latency data are useful in the diagnosis of optic neuritis,[2] which is often associated with multiple sclerosis,[3-6] and VER amplitudes are related to pattern and brightness perceptions.[7] This relationship allows the use of the VER for refractive error and acuity determinations,[8-12] assessment of recovery from photic and similar insults, and for other assessments requiring an objective measurement of perception/vision.[7] Usefulness of the VER as an assessment tool is somewhat compromised, however, because the amplitude of the evoked response is often quite unreliable; i.e., VER amplitudes change with no apparent subject, stimulus, or recording device changes.[13-16]

Four factors have been suggested to account for this variability: (1) data analysis procedures, (2) changes in the ocular status of the subject (e.g., accommodation, fixation, etc.), (3) changes in information processing occurring at central levels in the subject's visual system (e.g., changes caused by variations in cortical excitability)[17-19] and/or by correlates of the alpha rhythm,[20-24] and (4) changes in background noise occurring at the same frequency as the VER, hence recorded with it.

The literature is not very helpful in assessing the relative contributions of the factors. Van Brocklin et al.[16] have documented VER amplitude variability, but they made no attempt to correlate changes in amplitudes with changes in their subjects' perceptual and/or attentional states, nor did they consider the effects of noise on the VER. Because of this lack of available information, the following study was designed (1) to replicate Van Brocklin's study using an independent analysis system, (2) to investigate potential correlations between VER amplitudes and subjects' perceptual reports, and (3) to study

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the sources of VER variability using modeling techniques.

METHODS

One female and eight males served as subjects. Mean age was 29.1 years (range 20 to 39 years) and each subject was an experienced VER observer. All except BU were emmetropes or were corrected to 6/6 (20/20) or better. None except BU had significant visual anomalies or pathologies; BU had unilateral 6/60 (20/200) amblyopia of unknown etiology.

Subjects were seated comfortably in a darkened, shielded room 2.6 m from a 525 × 400 min arc Ayden model 8026 high resolution video system. This monitor uses a Mitsubishi model C-6912 video monitor with short persistence phosphors. A DEC 11-24 computer produced a black and white checkerboard consisting of 15 min arc checks on the display. Luminances of the actual checks were measured with a Gamma Scientific model 700 log-linear photometer system. The bright checks averaged 102.8 cd/m^2 (30 ft-L) and the dark checks averaged 15.42 cd/m^2 (4.5 ft-L).

To produce the evoked potentials, the display was square wave reversed at an alternation rate of 15 contrast reversals per second. This alternation rate was selected (in part) to synchronize with the refresh rate of the video system, thus preventing luminance artifacts on the display. In fact, no luminance fluctuations could be detected when the display was "integrated" by viewing it through a high-plus lens.

There was a small black dot in the center of the display which subjects were instructed to fixate except during rest periods between trials. Each subject viewed the display for 10 trials, each of which consisted of 60 sec of blank screen (with the same mean luminance as the checkerboard) followed by 80 sec of phase-reversing checkerboard; 1.5 min of rest were provided between trials.

Scales

To correlate gross variations in VER amplitudes with gross variations in the subjects' visual/perceptual conditions, each was asked to make four ratings immediately after each of the VER trials:

1. Attention: "Rate your degree of attention during the time the checkerboard was visible on a 1 to 7 scale, with 1 being groggy, 4 being relaxed but alert, and 7 being sharp."

2. Fixation: "Rate the percentage of time when the checkerboard was visible that you were able to hold your fixation on the center dot on the display screen."

3. Accommodation: "Rate the percentage of time when the checkerboard was visible that the entire display screen stayed clear and in focus."

4. Uniformity: "Rate the percentage of time when the checkerboard was visible that the display did not appear to move about in space, rearrange itself into small segments or patterns, or form diagonal or cross hatch lines."

These questions were discussed with each subject before any data were obtained and were repeated after each trial. Thus, each subject responded to each of the four questions 10 times.

Recording

Conventional procedures were used to record the VER's. Silver disc electrodes were attached to each earlobe and to the scalp, on the midline, 1.5 cm above the inion (electrode to electrode resistances were all 5,000 ohms or less). Outputs from the electrodes were differentially amplified (Grass model 7P511 amplifiers with frequency cutoffs, 0.1 and 100 Hz), and the analog data were stored on magnetic tape (Ampex model PR 2200 FM system).

Whereas specific procedures differ slightly in the experiments described below, typically the digitized VER data (digitization rate 256 Hz) were ensemble averaged and then analyzed using a fast Fourier transform (FFT). For each trial, the 90th sec (30 sec after the checkerboard first became visible to the subject) served as the beginning of the ensemble averaging period. The 90th sec was selected to allow initial transients and instabilities in the VER to pass.[25] After the 90th sec, samples of data ranging from 1 to 40 sec in length were averaged using 1.0-sec epochs (sweeps) and then Fourier analyzed to obtain the amplitudes of the 15.0 Hz VER components. The mean and SD of the 10 amplitude values for each subject/total sample length combination were then used to calculate variability indexes (VI).* For each set of 10 amplitudes, the VI is the SD of the values expressed as a percentage of their mean, as shown in Equation 1.

$$VI = \frac{SD}{Mean} \times 100 \qquad (1)$$

* Statistically, this same term is often called the Coefficient of Variation. It should be noted that variability is inversely related to reliability. Data which show considerable variability when determined using identical test conditions would be considered unreliable. An often confused term is "validity," which by definition is the extent to which a test measures that which it is intended to measure. It is possible for a test to be reliable but not valid and, to a lesser extent, the converse is also possible.

To show how the use of different FFT frequency resolutions would effect the variability of the VER's, all data were analyzed using 1.0 and 0.25 Hz wide frequency bins.

These analyses provided VI data, but because signal/noise ratios and 15.0 Hz noise variability data were also needed, the same analytical procedures were repeated for the noise data (obtained while the subjects were viewing the blank screen) except that noise analyses began with the 15th sec of each data trial.

RESULTS

Fig. 1 presents a summary of the nine subjects' mean 15.0 Hz VER and noise amplitude data (1.0 Hz resolutions) for 1.0 to 40 sec ensemble averaging periods. Both the VER and noise curves initially drop rapidly showing the effects of ensemble averaging, but beyond about 10 sec the curves flatten. The S/N curve, which shows the ratio of the mean VER amplitude to the mean noise amplitude for each averaging period, increases up to 40 sec where the mean S/N ratio is about 19/1 (median, 14.1/1).

To compare the reliabilities of the VER amplitudes across subjects and measurement conditions, VI's were used to normalize the data. Curves showing the relation of the mean VI values to the length of the data sample which was ensemble averaged are shown in Fig. 2. Also shown are additional VI data obtained in another laboratory under somewhat similar conditions.[16]

Several conclusions can be drawn from Fig. 2. First, VER amplitudes from trained, cooperative adults vary significantly; even more variability might be found in data from uncooperative subjects.[26] Second, there is little difference between the VI values found using 1.0 and 0.25 Hz resolutions. Third, the curves flatten when more than 20 sec of data are averaged.

FACTORS WHICH MAY ACCOUNT FOR VER VARIABILITY

VER amplitudes are variable even when subject, stimulus, and analysis conditions are held as constant as possible. Four factors were sug-

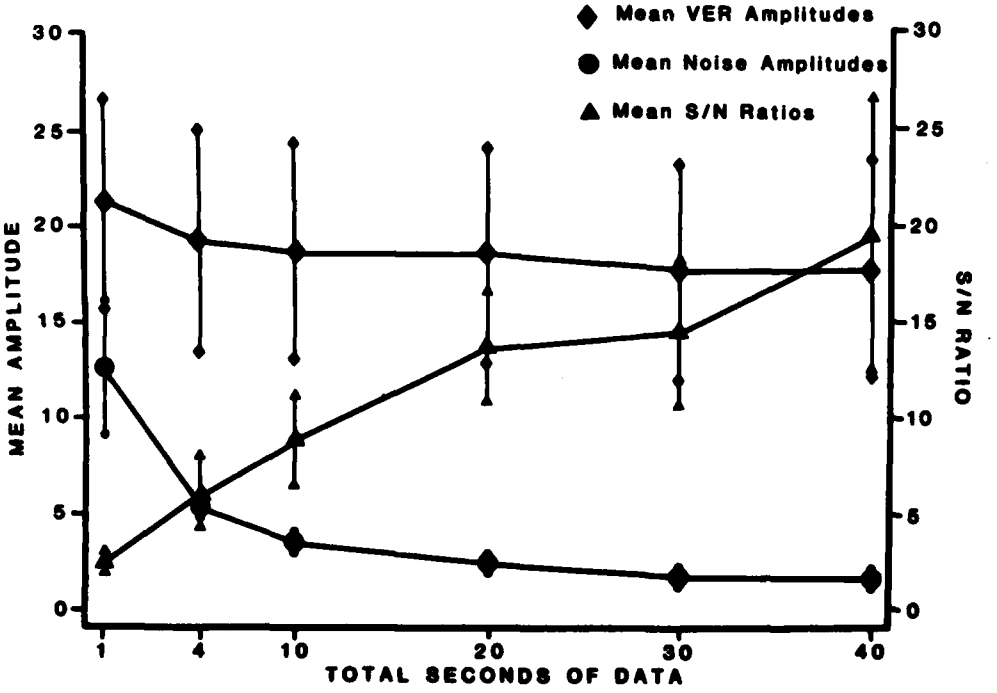

FIG. 1. Mean data from nine subjects are indicated by large symbols. Smaller symbols enclose a 1.0 SD range about each mean. The VER and noise curves demonstrate how changing the length of the total ensemble averaging period affects the amplitudes of these data. Beyond about 10 sec, increasing the total averaging period appears to have little effect on these amplitudes, but the S/N ratio increases steadily up to 40 sec [1.0 sec epochs (sweeps) were used to analyze all data].

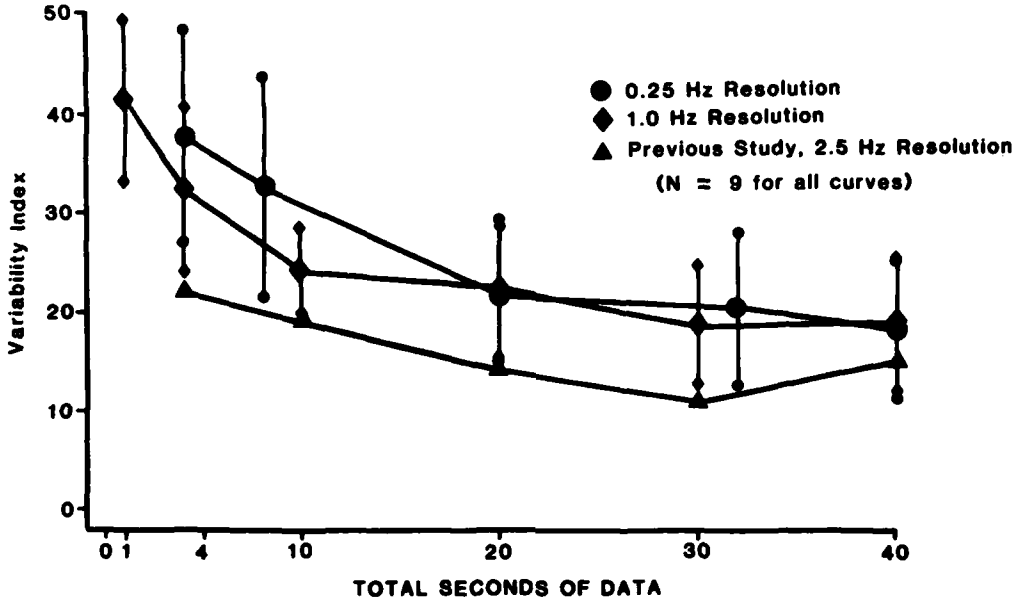

FIG. 2. Large symbols on the upper two curves represent mean VI data from this study using 1.0 and 0.25 Hz frequency resolutions. [Epoch (sweep) lengths of 1.0 and 4.0 sec, respectively]. Smaller symbols enclose 1.0 SD ranges. The curves show that beyond about 20 sec of data, both resolutions yield the same VI values. They also show that beyond 20 sec there is only a very gradual trend toward less variability with increasingly long averaging periods. Note that the number of epochs required for a given total averaging period is different for the 1.0 vs. the 0.25 Hz resolution analyses, and that the analyses are not independent because all were started with the 90th sec of data. The lower curve shows VI's from Van Brocklin et al.[16] obtained using nine subjects and 2.56 Hz resolution Fourier bins (384 msec epochs).

gested above to account for this variability and they can now be assessed individually.

Variability Associated with Data Analysis Artifacts

Variability could have entered via analysis procedures at several levels; e.g., data storage devices such as tape recorders could have caused artifacts, or the computer algorithms used to analyze the VER data could have been faulty. Subtle problems such as windowing, aliasing, and frequency drifts could also have caused the FFT to make the VER amplitudes appear variable.[27]

A number of quality assurance tests were conducted to ensure that these problems were not occurring. They involved repeated analyses of actual VER data and sine wave simulations, and the use of a low-pass analog filter to remove high-frequency signals which could be aliased to the 15.0 Hz VER frequency. These procedures demonstrated that less than 2% of the total VER variability could be accounted for by equipment artifacts.

A phenomenon which could cause artifactual variability is frequency drift of the VER signal itself which would cause "leakage" into frequency bins adjacent to that representing the VER signal. The amount of this leakage was determined empirically by using a 15.0 Hz sine wave which was then shifted sequentially in increments equal to 10% of the width of the Fourier bin. The data in Table 1 show the proportion of leakage for 1.0 and 0.25 Hz resolutions that resulted from this procedure. These data show that equal magnitude frequency drifts would have very different effects depending on whether 1.0 or 0.25 Hz bins were being used. If a significant amount of the variability present in the actual VER's was caused by frequency drifts, then the data obtained using 0.25 Hz bins should have been more variable than the data obtained using the 1.0 Hz bins. As was shown in Fig. 2, this was not the case.

Variability Associated with Changes in Ocular/Perceptual Status

Because the amplitude of the VER is considered to be an indicator of perception, any

TABLE 1. Leakage caused by frequency drift.

Frequency (Hz)		Proportion of Amplitude Represented in Bin with 15.0 Hz Center Frequency
1.0 Hz Bin Resolution	0.25 Hz Bin Resolution	
15.0	15.000	1.0
15.1	15.025	0.98
15.2	15.050	0.93
15.3	15.075	0.85
15.4	15.100	0.76
15.5	15.125	0.64
15.6	15.150	0.51
15.7	15.175	0.37
15.8	15.200	0.23
15.9	15.225	0.11
16.0	15.250	0.00

changes that affect stimulus clarity, brightness, contrast, or retinal location could affect VER amplitudes and be interpreted as variability. To provide a gross evaluation of this relationship, correlation coefficients were determined for subjects' ratings of attention, fixation, accommodation, and stimulus uniformity vs. their VER amplitudes (which had been normalized by converting them to Z-scores to remove the effects of the subjects' different means and SD's).

Scatter plot appearances and the near zero correlations (Table 2) show no significant relation between the visual/perceptual reports and fluctuations in the VER. This suggests that factors other than those associated with perception might be responsible for amplitude variability.

There may, however, be ocular changes which could affect VER amplitudes which may not be associated with perception. Examples are eye movements,[28-31] blinking,[32] and shifts in ocular balance. Armington has demonstrated blink evoked potentials,[32] so it is likely that blinks occurring during the stimulus viewing period could cause artifacts. To assess the importance of this factor, blink rates were measured by gross electromyogram recording for three subjects representing high, medium, and low VI scores. All three subjects blinked only two to four times per minute during the checkerboard viewing period; thus, the results of these blinks would not have major or differential effects on VI scores.

Because all the VER data were obtained under binocular viewing conditions, variability caused by shifts in ocular dominance cannot be assessed.[33,34] It can only be noted that subject B. U., who was a 6/60 (20/200) amblyope, and who presumably had relatively stable dominance, showed as much variability as the other subjects. Binocularity and eye movements, however, must remain possible sources of variability pending further investigation.

Variability Associated with Changes in Central Processing

It has been suggested that the amplitude of the VER is modulated by (or at least correlated with) certain electroencephalogram (EEG) signals. For example, a significant relation between VER amplitude and alpha rhythm (8 to 13 Hz EEG activity) has been proposed by some[20] and denied by others.[22] Theoretical predictions indicate a negative correlation between the VER and alpha rhythm, but actual measurements in normal subjects often yield a slight positive correlation (References 21 and 24 and R. L. Yolton, unpublished observations).

To investigate the relation between VER amplitudes and other EEG frequencies, a Fourier transform was used to obtain a frequency spectrum (1.0 Hz resolution) and the 1.0 to 14.0 Hz EEG activity occurring during the 40 sec period of each trial for which VER data were obtained. These EEG amplitudes were then correlated with the corresponding VER amplitudes across the 10 trials for each subject. None of the r values thus produced reached significance at the 0.01 level. This lack of significant correlation values suggests that, at least in a normal population, VER amplitudes cannot be shown to be modulated by, or otherwise directly associated with, EEG frequencies up to 14.0 Hz.

As a second test for amplitude modulation, data from four separate 16.0 sec epochs for two subjects were analyzed using an FFT which produced 0.0625 Hz resolution. If sinusoidal amplitude modulation of the 15.0 Hz VER was occurring, the FFT power spectrum would show a pair of frequency peaks displaced equal distances above and below the 15.0 Hz VER peak. Fig. 3 reveals no such peaks in the data from subjects E. L. and D. U. There is no consistent, sustained amplitude modulation of the VER detectable in the data from these two subjects.

In a third test for amplitude modulation, a sample of data from subject D. U. was used. The raw VER data were analog filtered (Rockland bandpass filter, 14–16 Hz) to produce a cycle by cycle plot. Gross observation (Fig. 4) and a Fourier analysis of these variations revealed no evi-

TABLE 2. Ratings vs. VER Z-scores.

VER vs.	Mean Correlation Coefficient	Significance
Attention	0.0017	NS
Fixation	0.001	NS
Accommodation	0.01	NS
Uniformity	0.0007	NS

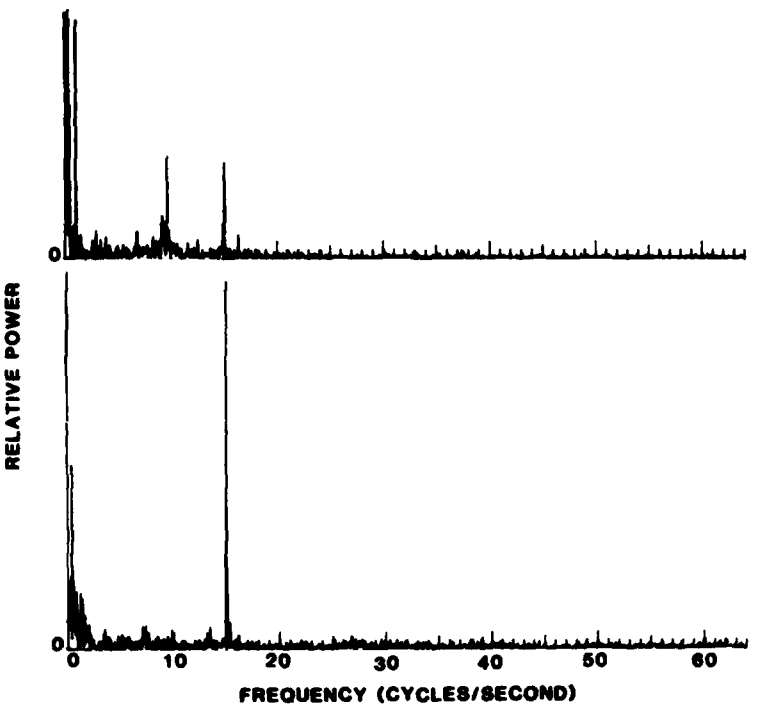

FIG. 3. Power spectra from subjects E. L. (upper) and D. U. (lower). Each trace represents 16 sec of data analyzed using 0.0625 Hz bins. E. L. shows alpha activity at about 9.0 Hz and both show VER's at 15.0 Hz.

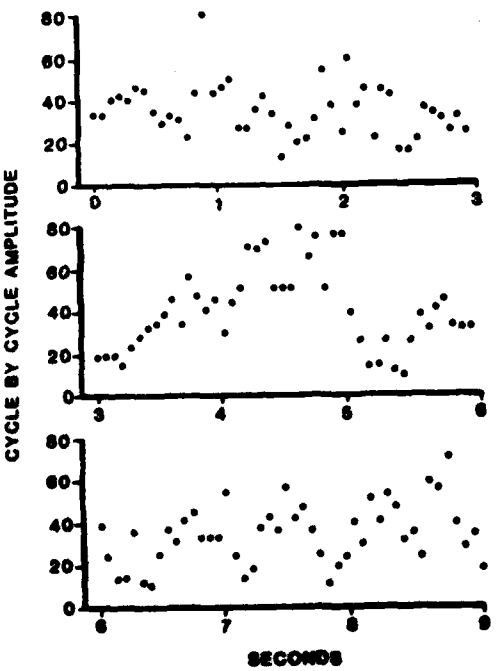

FIG. 4. Cycle by cycle amplitudes for subject D. U.

dence of amplitude modulation. Thus, while amplitude modulation of the VER might exist in short bursts (considerably less then 9.0 sec), such modulation is not constant enough to be detected using a Fourier analysis.

It is also clear that the cycle by cycle variations of the VER are poorly related to the subject's perception as she strongly disclaimed any fluctuations in the appearance of the stimulus which might be related to the 600% changes in amplitude that occurred during the 9.0 sec viewing period. If cycle by cycle amplitude changes are related to perception, other mechanisms in the visual system must be designed to remove their effects.

Variability Associated with Noise

The ensemble averaging process is designed to minimize the effects of nonsynchronized noise which is recorded along with the VER and, neglecting leakage, the FFT eliminates noise with frequencies outside the Fourier bin containing the VER. These two techniques do not, however, eliminate all noise contamination. The amplitude values provided by the FFT may be considered to be the sum of the actual VER plus the noise, with each having a certain mean amplitude and variability.

Although it is not possible to directly ascertain the fraction of the measured VER which is caused by noise, a determination of the noise amplitude and variability was made on each trial during the period just before the subject viewed the reversing checkerboard (Fig. 1). An extensive discussion of the effects of this noise on VER variability will be presented in the section below on modeling.

Other Factors

Because the VER amplitudes and the VI's for the nine subjects were individually quite different, intersubject differences were correlated with body physiology and age. To make these determinations, correlations relating VI's, S/N ratios, and mean 40 sec VER amplitudes to the subjects' ages and their height to weight ratios were determined as shown in Table 3. The significant negative correlation between VER amplitude and age is somewhat surprising because of the limited age range represented by the subjects (20 to 39 years), and is not easy to explain. Decreases in skin conductance with increasing age cannot be the cause of the relationship as all subjects had approximately equal electrode resistances, nor can relative body build as the height/weight ratio was not correlated with amplitude.

There are many other potential sources of VER variability, but few data exist to substantiate or refute their relation to the VER. These factors include respiration and heart rates, blood flow to the cortex, time since the last meal, psychological state,[1,35] drugs the subjects may have taken,[36,37] etc. One study[38] has even shown that by having the subject imagine or hallucinate objects which come between her and the display screen, the VER could be diminished or extinguished.

In the present study with normal subjects, the variations in psychological state, blood sugar, and cortical physiology that might have occurred during a single recording session would seem to be too small to have affected the VER's in any significant way, but further data are needed to allow definitive statements to be made about the effects of such subtle factors.

TABLE 3. Age, S/N, and height/weight vs. VI correlations.

Comparison	r Value	Significance
Age vs. VI	0.32	NS
Age vs. amplitude	−0.68	$p < 0.05$, $dF = 7$
Age vs. S/N	−0.64	NS
Height/weight vs. VI	0.23	NS
Height/weight vs. amplitude	−0.23	NS
Height/weight vs. S/N	−0.49	NS

MODELING

Because it was difficult to experimentally separate the effects of the many factors which contributed to VER variability, a simulation approach was used in which two additive sine waves were used to model the recorded VER.[39] In the model, it was assumed that the steady-state VER (VER_R), as was recorded from the subjects described above, was the sum of two components: a "true" VER sinusoid (VER_T) representing the activity of the visual system, and a noise sinusoid (N) representing the residual noise which remained after ensemble averaging and Fourier transformation. The frequencies of VER_T and N were assumed to be equal, and, to simulate the "constant" perceptual appearance of the checkerboard stimulus over relatively short viewing periods, the amplitude of VER_T was kept constant. The amplitude of the N sine wave was varied, however, because data recorded from the nine subjects showed that the actual amplitude of the noise (recorded during the period just before checkerboard viewing) varied from trial to trial; thus, this noise variability was incorporated into the model.

In the modeling process itself, a Data General computer was used to add together the VER_T and N sine waves; each addition of VER_T and N produced a VER_R simulation. These VER_R simulations were produced in sets of 10 each to simulate the 10 trials during which the subjects' VER data were recorded. Obviously, the amplitudes of the 10 VER_R waves were dependent on the phase relation between the VER_T and N waves at the time of addition and, as there was no reason to assume a fixed phase relation, the relation was varied randomly before each addition. Varying this relation produced a considerable degree of variability in the VER_R amplitudes.

Additional variability was produced by changing the amplitude of N before each addition. Ten different N amplitudes were used to provide an N variability index of 62.5% (which was equal to the mean noise VI for the nine subjects).

The computer was programmed to produce 100 sets of 10 VER_R simulations and then to calculate the VI's for the 100 sets. It made these calculations for different mean N values so as to produce mean S/N ratios ranging from 2.5 to 57, as shown in the upper portion of Fig. 5. Also shown is a zone enclosing plus and minus 2 SD's from the mean VI values.

The lower portion of Fig. 5 shows the VI's for the nine subjects. The computer modeling pro-

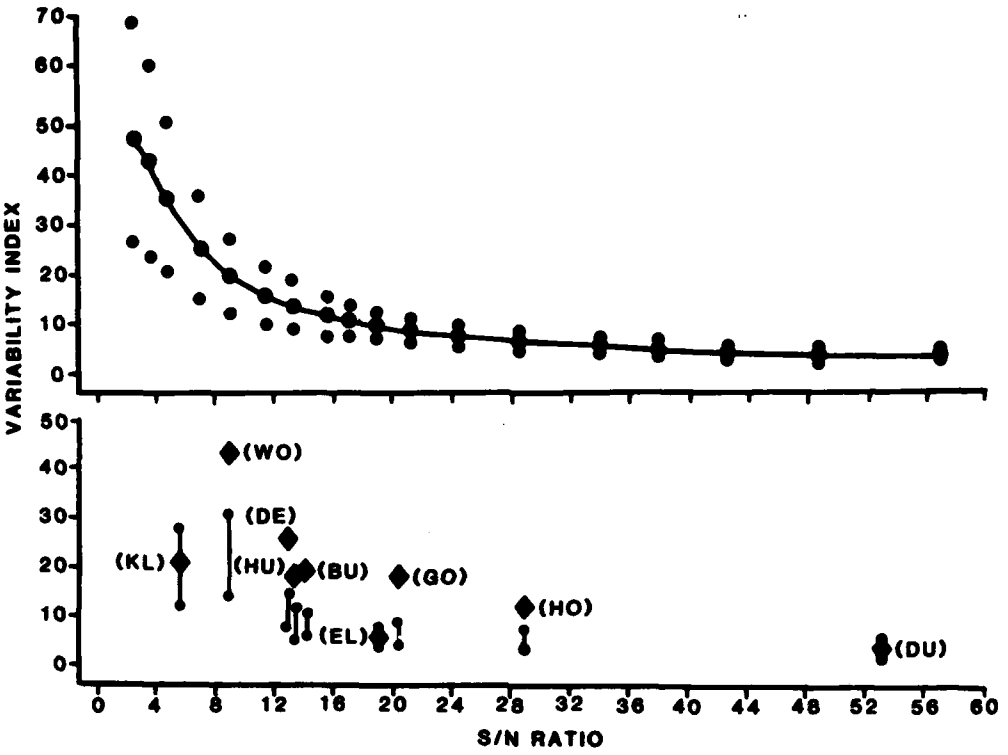

FIG. 5. Results of modeling. In the upper portion, large filled circles represent VI values obtained with phase and noise amplitude variability (noise VI 62.5%). Small filled circles indicate plus and minus 2 SD's from these means. Each S/N ratio is determined by calculating the mean of the individual S/N ratios for 1000 VER_n simulations. In the lower portion of the figure, the filled diamonds show data for individual subjects. The filled circles show the plus and minus 2 SD ranges of the computer predictions for each subject's data. Predictions are based on subject's individual S/N and noise VI data.

gram was used to predict the expected mean VI value (and plus and minus 2 SD zone) separately for each subject's individual S/N ratio and noise VI. VI's for three of the subjects are in the predicted zones; however, six are considerably above their zones. Thus, if the modeling approach is valid, either the variability of N increased during the time these six subjects were actually viewing the checkerboard (as compared to the time just before the checkerboard became visible), or there was variability in VER_T itself for them, or there was a third, and as yet unknown, component which must be added to VER_T and N to yield VER_n. Although the modeling approach does not allow separation of these three possibilities, it is important as it does show that reliable VER's cannot be expected when data have low S/N ratios.

There are a number of ways to decrease the variability of VER data but the most commonly used method is simply to ensemble average more epochs until the desired level of reliability is achieved. For a given subject, a theoretical approximation of how many epochs would be needed to reach a desired level can be made if the S/N ratio for a sample of M epochs of data is known. Equation 2 indicates how the S/N ratio changes as a function of the number of epochs ensemble averaged[27] and the S/N ratio for the subject's M epochs of data.

$$S/N_{(\text{one epoch})} \times \sqrt{M_{(\text{No. of epochs averaged})}} = S/N_{(\text{M epochs})} \quad (2)$$

Using this equation, the S/N ratio for one epoch can be calculated. Next, the desired VI is specified, and the S/N ratio required for this VI is determined. Finally, with the S/N ratio for one epoch and the required S/N ratio determined, equation 2 can be solved for M which gives the total number of epochs which must be ensemble averaged to produce the desired reliability.

These calculations assume perfect subjects and do not consider artifacts which may make

TABLE 4. Actual and predicted data.

Subject	Actual Data		Predicted Data		
	Mean S/N ratio for 40 epochs	S/N ratio for 1 epoch	S/N ratio required for VI of 5%	Epochs required to reach VI of 5%	Total time (in min) to reach VI of 5% assuming 1.0 sec epochs
DU	52.9	8.4	21.5	18.3	0.3
GO	19.3	3.1	33.4	50.0	0.8
HO	29.0	4.6	22.4	46.9	0.8
BU	13.4	2.1	40.0	98.1	1.6
EL	20.4	3.2	29.4	58.5	1.0
HU	14.1	2.2	24.0	117.0	2.0
KL	5.6	0.9	21.0	630.6	10.5
DE	13.2	2.1	35.9	198.4	3.3
WO	8.9	1.4	24.6	763.1	12.7

data more variable than predicted theoretically. The calculations also do not take into account the fact that very long observation periods could produce habituation or fatigue resulting in decreases in VER amplitudes and S/N ratios.[1]

To show how these calculations apply to real subjects, data from the nine subjects described above can be considered. For each subject, the S/N ratio for one epoch is determined by using equation 2 and this is used to approximate the number of epochs necessary to achieve a VER amplitude VI of 5%. (Note that the S/N ratio required to reach the 5% level is different for each subject because their individual noise VI's were used in calculating the ratios.) Table 4 shows that for several of the subjects, an excessively large number of 1.0 sec epochs would need to be averaged to produce data with this degree of reliability.

Thus, use of two relatively simple relations (VI vs. S/N ratio, and S/N ratio change vs. number of epochs averaged) allows predictions to be made with respect to the total averaging time necessary to produce VER's with predetermined degrees of variability. These relations should be used with caution, however, because of the factors described above including artifacts and habituation.

DISCUSSION

In 1979, Van Brocklin et al.[16] quantified what most VER researchers already knew—the amplitude of the VER is variable. The subjects in the present study were found to be even more variable than Van Brocklin's and this degree of variability is sufficient to render questionable the use of steady-state VER amplitudes for the reliable assessment of vision. Certainly, the amplitude changes associated with eyes-open vs. eyes-closed conditions can be discriminated in most subjects, but the rating scale data show no correlations between VER amplitude fluctuations and fairly large changes in attention, ocular status, and stimulus perceptions. The lack of correlations suggests that the amplitude of the VER may be significantly affected by nonvisual factors.

Earlier in this paper, four major factors were identified which might contribute to VER variability: analysis procedures, ocular status, central processing, and noise. Based on quality assurance testing, it was shown that artifacts associated with recording devices and computer programming did not contribute significantly to the variability; neither did VER frequency drifts nor FFT artifacts such as aliasing. The signals that were processed and the resulting data were valid representations of events occurring in the proximity of the recording electrodes.

Although processing equipment cannot account for a significant proportion of the VER variability, the noise which was recorded and analyzed along with the VER can. In the modeling experiment, it was shown that essentially all the variability in the data from three of the subjects could be accounted for by assuming only a random phase relation between variable amplitude noise and constant amplitude true VER components. For these three subjects, the only way to significantly increase the reliability of their data would have been to increase their S/N ratios. As noted, this could be done by using longer ensemble averaging periods. However, long periods would make it difficult to follow rapidly changing visual phenomena. Also, with very long averaging periods, subjects tend to habituate or become restless and may produce artifacts associated with gross body movements. These large amplitude artifacts might be removed by the use of an active rejection system,

but the effects of such artifact rejection cannot be estimated.

Data from six subjects showed more variability than could be accounted for by the model. For these subjects, ocular, eye position, or central nervous system changes may have added variability. Undoubtedly, each of the subjects experienced changes in her/his ocular status during the stimulus viewing period, and fixation drifts, changes in pupil size, blinking, and similar factors clearly have the potential for affecting the amplitude of the VER. However, findings such as the subjects' low blink rates and the lack of correlation between the ocular status rating scales and the VER amplitudes make it difficult to conclude that a significant proportion of VER variability was caused by changes in these functions. Further work in this area will be needed to demonstrate whether the modeling assumption of no variability in VER_T is valid or if it must be modified.

It was also not possible to demonstrate a consistent relation between the subjects' central nervous system processing of the VER checkerboard image and amplitude variability. No EEG rhythms, including alpha, were consistently correlated with VER amplitudes and there was no correlation with the subjects' attention ratings. Major changes in attention, such as might be produced by a threat of electric shock, could change VER amplitudes,[40] but the smaller attentional fluctuations reported by the subjects did not seem to have this effect.

The lack of correlation between VER amplitudes and perceptual reports, and the inability to find any EEG signals which covaried with the VER, raise doubts about major contributions of changes in cortical processing to VER variability. Although negative evidence does not prove the lack of a relation, the effects of changes in cortical processing, in a controlled situation, do not seem large.

CONCLUSIONS

We conclude that a major proportion of the variability shown by the subjects used in this study is caused by noise analyzed along with the VER. For three subjects, no other factor need be considered to explain all their variability. For the others, noise plus some combination of artifacts may be used to explain the variability. Additional work will be needed to separate the relative contributions of these artifacts.

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The reliability of steady-state visual evoked responses (VER's) was determined for nine normal subjects using Fourier analyses with 1.0 and 0.25 Hz bin resolutions. No correlations were found between VER amplitudes and subjects' reports of attention, accommodation, fixation, or perceived organization of the stimulus. Across subjects, there was also no sustained amplitude modulation of the VER by any frequency (including alpha), and frequency drift of the VER did not contribute significantly to its amplitude variability. Modeling, using mixed sine waves to simulate different signal/noise (S/N) ratios, established that a significant portion of VER amplitude variability can be accounted for by noise which occurs at the same frequency as the VER and which is not removed by ensemble averaging.

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