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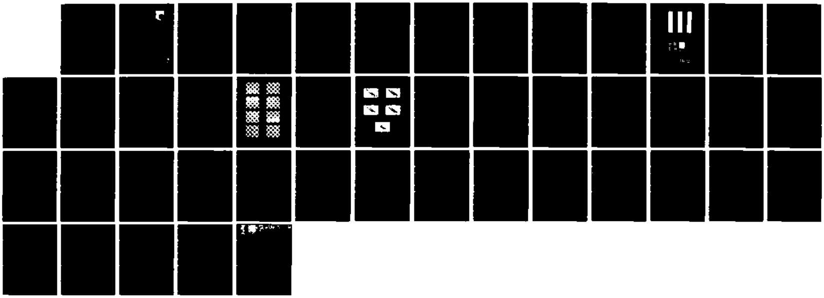

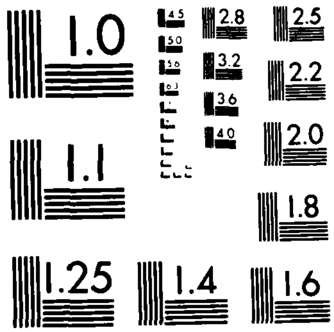

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UTILITY OF THE CORTICAL EVOKED RESPONSE AS A MEASURE OF PHOTOGRAPHIC IMAGE QUALITY

Colonel R. D. O'Donnell
AF Aerospace Medical Research Laboratory

Thomas Stanzione, Lloyd G. Clark, Edward L. Gliatti
AF Wright Aeronautical Laboratories

Robert Love & Julie Klug
System Research Laboratory

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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This technical report has been reviewed and is approved for publication.

Edward L. Gliatti

EDWARD L. GLIATTI, Chief
System Engineering Group
Sensor Evaluation Branch
Mission Avionics Division

James C. Haley

JAMES C. HALEY, Chief
Sensor Evaluation Branch
Mission Avionics Division
Avionics Laboratory

FOR THE COMMANDER

ROBERT E. DEAL, Assistant Chief
Mission Avionics Division
Avionics Laboratory

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This report covers the results of investigations by AMRL into the use of Cortical-Evoke Potentials to measure Photographic Image Quality. This work was sponsored by the Avionics Laboratory using Laboratory Director's Funds.

Cortical Evoked Response (ER) procedures (both steady-state and transient) were tested for their utility and sensitivity in indexing the focus level of various kinds of targets. Four studies investigated the ERs generated by presentation (cont'd) of Air Force tri-bar photographs, checkerboard patterns, and complex real imagery. Neither low nor high frequency steady-state ER amplitudes showed sensitivity to defocusing of any type of imagery, although contrast ratio clearly produced differences. The phase delay of the fundamental steady-state ER changed significantly with focus of a single tri-bar target. Transient evoked responses showed systematic changes in amplitude as a function of focus. A negative going peak between 90 and 170 msec. after the stimulus appeared to diminish in amplitude with increasingly poorer focus of both checkerboard and complex imagery. Results indicate that, under conditions tested, the steady-state ER does not appear to be a promising technique for assessing image focus, while the transient ER seems considerably more reliable and valid. Suggestions for further development of this procedure are discussed.

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SECTION I

INTRODUCTION

Many operational situations in the U.S. Air Force generate photographic imagery. The quality of this imagery becomes a crucial variable in determining the confidence which can be placed in interpretations made from such photographs. At the USAF Sensor Evaluation Center, several techniques to assess image quality are currently used. Those that introduce a human into the analysis most often use psychophysical judgment in which, for instance, an analyst must match a particular segment or edge in a photograph to a standard. There is a continual need to improve techniques for assessing such imagery, and considerable interest in developing more objective ways of doing so without sacrificing the variability and creativity provided by the human component.

A relatively new technique, which has enjoyed considerable success as a measure of sensory and cognitive processes, is the cortical evoked response (see Regan, 1972; O'Donnell, 1978, for reviews). Several types of visual evoked response (VER) have been described, and each type provides sensitivity in measuring certain aspects of visual sensation and information processing. The "transient" evoked response represents the reaction in the brain which occurs up to about 750 milliseconds after a discrete stimulus. This response can be broken up into separate segments representing the brain's reaction to the sensory qualities of the scene being viewed (color, sharpness, contrast, etc.) (Perry and Childers, 1969) and a component that appears to reflect the cognitive activity being carried out by the individual (Beck, 1975). As early as 1970, Harter and White (1970) demonstrated that a particular set of peaks seen in the transient-evoked response showed maximum amplitude when the scene being viewed was in focus. Using this technique, they were able to develop a procedure for determining the spherical correction necessary to assure optimal visual acuity. Considerable work has subsequently defined the sensitivity of these early components of the transient evoked response to sensory qualities of an image in considerable detail.

A different type of visual evoked response has been described by Regan (1972 and 1977). This technique, called the "steady-state" evoked response, presents a visual stimulus rapidly (faster than four times per second) and analyzes only the portion of the brain's activity that becomes synchronized to the flickering stimulus (Wilson and O'Donnell, 1981). Since the data analyzed in such a procedure is narrowly constrained in the frequency domain, the variability within a subject and between subjects is reduced considerably. In addition, a sample of the steady-state evoked response can be obtained in a relatively brief period of time, with a light flickering at a rate that is not obtrusive to the individual. Speckreijse (1973), Moise (1980), and Wilson and O'Donnell (1981) demonstrated that an adequate steady-state evoked response can be obtained to a visual stimulus flickering so fast that the human cannot perceive the flicker, i.e., above the critical flicker fusion point. Further, the steady-state evoked response appears sensitive to many of the same sensory characteristics measured by the transient evoked response. Thus, Regan (1973) demonstrated that both the spherical and cylindrical corrections for eyeglasses can be determined quite accurately using a rapid steady-state evoked response procedure (Marg, 1976).

In view of the continued interest in developing objective measures of the perceived quality of a photographic image, it appears reasonable to consider the evoked response in all of its various forms as a candidate for such a measurement technique. Although previous research has established a firm relationship between visual acuity and evoked-response parameters, it is not certain that such measures could be used in a practical way with respect to photographic imagery. Most of the previous work illustrating the relationship between visual acuity and evoked responses has been carried out with optical lenses introduced in front of the subject's eyes, with an otherwise sharp image. In addition, the image itself has been relatively simple (sinewave gratings or checkerboard patterns) in order to maximize the effect. Procedures have been designed to produce a sampling over a wide range of acuity values, and the independent variable has been the subject's acuity rather than the quality of the imagery. Finally, there is a question of whether the procedure utilized to generate an evoked response, i.e., flickering lights, could be so obtrusive to the subject as to make the technique nonusable.

The present series of studies represents the initial efforts in an attempt to determine whether laboratory procedures for generating the cortical-evoked response can be validated with respect to photographic imagery, particularly of complex scenes, and also whether such procedures can be adapted to field use. If such an application could be demonstrated, subsequent studies could explore the precise nature and limits of this approach. Ultimately, on-line monitoring of operator efficiency could possibly be used by photo interpreters to warn of missed targets, inadequate imagery or impending fatigue. Similarly, on-line enhancement of the individual's physiological status through closed-loop biocybernetic control would become feasible. The overall program, therefore, calls for:

1. Laboratory test of the sensitivity of the evoked response techniques in indicating differences in focus of standard imagery used for calibration by the Air Force.

2. Determination of the most practical and sensitive measurement techniques for assessing such imagery.

3. A series of experiments utilizing increasingly complex imagery to generate the evoked response, with evaluation of the validity and sensitivity of the response for each kind of imagery.

4. Exploration of techniques for making acquisition of this measure practical in field settings.

The present report details the procedures and results of four exploratory studies dealing primarily with the first three goals noted above.

SECTION II

APPARATUS AND PROCEDURE

All experiments reported herein were conducted in the Neuropsychological Laboratory of AFAMRL. The basic procedure involved presentation of the visual stimulus through a back-lighted viewing screen by a slide projector. The subject was seated comfortably in a sound-attenuated room and, both, brain waves and, in some cases, behavioral responses were recorded from the subject. The subject's task was to view the imagery and either to maintain fixation or to make a decision concerning the quality of the imagery. Brain activity evoked by the visual imagery was amplified, analyzed, and recorded automatically.

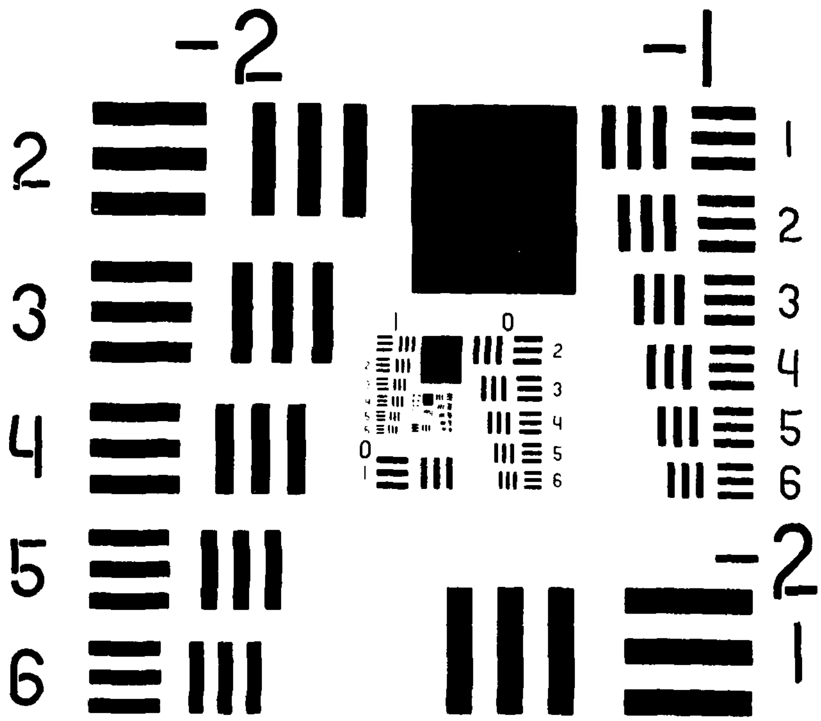
1. STIMULUS MATERIAL AND PRESENTATION

For the first two experiments reported here, the master target consisted of a USAF 1951 Resolution Target (MIL-STD-150A, 1959) on a glass plate. This was photographically reduced onto Kodak Panatomic-X Film using a 35 millimeter Nikon F Camera with a 55 millimeter Micro-Nikkor lens on a copy stand. The master target was back-lighted using a light table. Multiple exposures at various focus settings produced a range of resolutions. Multiple contrasts were obtained by changing exposure times. Two types of slides were produced by this procedure. In one, the whole target was photographed, including all of the various tri-bars in the resolution target (Figure 1, lower half). In the second type of slide (Figure 1, upper half) the largest bar group (-2, element 1) was photographed in such a way as to produce a bar and space width of 2 millimeters. This produced a 2-degree field-of-view when projected to the subject. The film was processed in Kodak D-76 developer at 20°C for 5 minutes and mounted in cardboard mounts.

Densities of the bars and background were measured using a MacBeth TD-105 Densitometer with a 2-millimeter aperture. The large density patch was measured to obtain the densities of the bars. Contrast ratios of the target were calculated by the formula:

$$C.R. = 10(D_{max}-D_{min})$$

b. Single Tri-bar (Experiment 1)



a. Whole Target (Experiment 2)

Figure 1. Resolution Chart

The targets were placed on a Mann Model 422 Comparator and the bar and space widths were measured. The "just resolved" group and element of each target was found using three IRARS-trained photo interpreters (Manual for Standardized Assessment and Expression of Tribar Resolution, DIA, 1975). The bar and space widths were used to convert these into limiting resolution in line pairs/millimeter.

For the first experiment, only the single tri-bar slides were used. Neutral density filters were added to some of the slides in order to equate space average luminance for the entire scene viewed by the subject. In the first experiment, a mask was placed over each slide to eliminate scattered light and to insure that only the target tri-bar was viewed. For the second experiment, this mask was removed since it appeared to provide a sharp edge to the subject, even with degraded imagery. In its place, a diaphragm aperture was placed in the optical path of the projected image. This blurred the edge of the mask; yet insured removal of ambient light. No masks were used with slides showing all tri-bar gradings.

In the above way, a total of 40 slides were produced showing a single tri-bar, and 8 were produced showing the entire resolution target set. Five contrast levels were selected, and eight slides with differing resolutions were produced at each contrast level. The contrasts and resolution of each slide are shown in Table 1 for both the single tri-bar and for the entire resolution target.

Stimuli were presented through a Scientific Prototype 3-channel tachistoscope, using two Kodak random access slide projectors. The slide projector focus was set manually for the maximum resolution target. However, for each slide, the automatic focus feature of the projector would attempt to generate optimal focus; and it must be assumed this was constant for any given slide since no specific measurement was taken for every slide presentation.

TABLE 1

CONTRAST AND RESOLUTION FOR ALL SLIDES

Contrast	Resolution (cycles/mm)							
				Single Tri-Bar				
1.5	26.9	10.7	7.3	5.3	4.4	3.2	2.7	2.2
1.9	26.9	12.0	7.8	5.5	4.4	3.5	2.8	2.4
2.6	26.9	12.5	7.8	5.5	4.4	3.5	2.8	2.4
3.3	22.2	12.5	7.8	5.5	4.4	3.5	2.8	2.5
6.1	23.1	12.5	7.6	5.5	4.4	3.5	2.8	2.5
				Whole Targets				
13	24.4	12.3	7.7	5.4	3.9	3.1	2.4	1.9

The optical path of the slide projector was interrupted by a rotating disk driven by a constant-speed motor (monitored continuously). Disk speed could be adjusted to produce a desired flicker rate of the stimulus material. Uniblitz shutters on the slide projectors were opened by the operator on a random schedule when the subject was attending and after assuring correct disk speed and slide presentation.

The subject was seated inside an IAC electrically shielded attenuated chamber. Beckman Biopotential Miniature Electrodes were attached over the central occipital (O_z) region and on both mastoids (Jasper, 1958). The Electroencephalographic (EEG) signal was amplified by Grass P511 amplifiers with a bandpass of 0.1 to 100 Hz. This signal was then fed into a Nicolet C-1000 signal averager and into a Nicolet 660 A Dual-Channel FFT Analyzer. All raw EEG data were stored on a Honeywell 1-inch analog tape recorder (Model 5100 C). Stimulus presentation, recording of behavioral responses, and data management were under the control of an Intel microprocessor and Silent 700 computer terminal.

2. PROCEDURES

Subjects were thoroughly briefed concerning the procedures and purposes of the study and signed informed consent prior to participation. Contact electrodes were placed in the appropriate positions, with resistance between the electrodes lower than 2K ohms. For the first experiment, subjects were instructed to view the eight complete resolution target slides which had been placed in random order in one of slide projectors. Subjects were able to view each slide for as long as desired and to control the advance or reverse movement of the slide projector so as to view any slide any number of times. The subject's tasks was to rank order the slides in terms of overall image quality, using 1 for the best quality and 8 for the worst. Subjects were permitted as much time as necessary to perform this task. In performing this task, subjects were instructed not to determine the limiting resolution of the slide (which is the usual task of photo interpreters) but to judge the slide on "how good it looked." These subjective rankings of slides were obtained to assure that the resolution levels chosen for each image were ordinally separable by the subjects. No EEG data were taken during this subjective classification. These subjective ratings were obtained prior to each session for each subject, and they were obtained only in the first experiment.

a. Experiment Number 1

Ten subjects were used in the first experiment. Five of these were experienced photo interpreters and five were unfamiliar with photo interpretation procedures. Visual acuity was measured, and revealed wide variability in subjects, ranging from 20/20 binocularly to 20/100 for one subject uncorrected. For the photo interpreter subset, no attempt was made to control for acuity, and each individual was permitted to view the imagery in the way reported to be most comfortable. For the non-photo interpreters, all subjects were 20/20 or corrected to 20/20 during testing.

Subjects first performed the rank ordering procedure described above, and were given as much time as necessary to complete this task. The main part of the experiment was then begun. The single tri-bar image was presented to the subject for approximately 45 seconds. No behavioral response was required. The rotating disk produced a flicker of the image at one of two speeds described below. The FFT analyzer selected overlapping EEG epochs and performed multiple fast Fourier transforms on the EEG produced while viewing each tri-bar. These FFTs were then averaged to produce the composite FFT for that trial. This composite was used for analysis. The frequency of the spectral analysis at the flicker rate of the stimulus was inspected, and its amplitude and phase angle were recorded.

The subject viewed 40 slides in one session. A 10- to 15-minute break was then given, and a second session was begun. These two sessions together lasted approximately 2.0 to 2.5 hours, and this constituted the subject's participation for one day. Three days of participation were required to complete the entire series of slides. Therefore, a grand total of 240 stimuli was viewed by each subject. These consisted of eight focus levels at each of five contrast ratios presented at two flicker rates, with three repetitions for each slide. The data for the first experiment are, therefore, based on a grand total of 2,400 stimuli.

The flicker rate of the slide was either 8 Hz or a frequency between 48 and 54 Hz chosen in the following way. Each subject was exposed to a flickering light set at 48 Hz, and the amplitude of the subject's steady-state brain response to the stimulation was determined. The flicker rate was then changed to 50 Hz and a similar determination was made. The same procedure was carried out for 52 and 54 Hz. Individuals typically show higher amplitude at some frequency within this range (Wilson and O'Donnell, 1981); and for each subject, the frequency yielding the highest amplitude response was selected. This then provided the stimulating frequency at the upper end for that subject for all slides in the experiment. For stimulation at 8 Hz, the FFT analyzer averaged eight overlapping epochs of 4-seconds duration (2-second overlap) in order to produce final spectral values. For the upper frequency stimulation, the analyzer selected 16 epochs of 2-seconds duration (1-second overlap) to produce the final estimate.

b. Experiment Number 2

Four subjects were used in the second experiment. These were not experienced photo interpreters. However, they had participated in the first experiment and were very familiar with the evoked response laboratory and procedures. The visual acuity of the subjects was 20/20 or better, or corrected to 20/20.

In this experiment, stimuli consisting of both a single tri-bar and those consisting of all the tri-bars in an entire resolution target were used. Only one contrast level was used, for the single tri-bar stimuli, corresponding to the 6.1 contrast series shown in Table 1. The same eight levels of focus or resolution were used.

Two separate subsets of data were collected during this experiment. In one, the steady-state evoked response was generated in the same way as described previously for Experiment 1, with the exception that only 8 Hz stimulation was employed. Each of the eight tri-bar slides and the eight whole target slides were flickered while the FFT analyzer selected 8 overlapping epochs of 4 seconds each. Three repetitions of each slide were performed. In this procedure, the slide is flickered for 5 seconds prior to the initiation of data sampling in order to insure the steady-state condition. For this experiment, as in the first experiment, the individual EEG records were averaged by the CA-1000 Signal Averager, using a 500-millisecond sampling duration and triggering on the first stimulus after each 500 milliseconds.

In addition to the steady-state evoked response, transient evoked responses were obtained during this second experiment. Each of the tri-bar and resolution target slides were flashed to the subject for 1 second (with a variable intertrial interval between 5 and 10 seconds). The slide was presented in this way 32 times, with between 2 and 5 "catch trials" interspersed randomly during the presentations. The catch trials consisted of the same tri-bar or resolution target as the basic stimulus, but presented horizontally rather than vertically. A subject's task was to detect these catch trials and to respond to them by pressing a button. This procedure was used simply to insure subject attention and to attempt to generate late components of the evoked response as the subject carried out the discriminative task. For this set of data, a chin rest was used to assure subject's head position. In addition, a small fixation point was provided between trials to assure eye fixation. During the intertrial interval, a second slide projector maintained the same space average luminance provided by the stimulus so that stimulus appearance did not create any overall change in luminance. Data for the transient evoked response experiment was analyzed manually. The 32 EEG samples generated during the presentation of each slide were averaged by the Nicolet CA-1000 and were printed out on a X-Y plotter. Amplitude measures were read directly for each major peak in the wave form and were compared across focus levels and between tri-bar and resolution target stimuli.

c. Experiment Number 3

The stimuli were made in the same way as the tri-bar stimuli, except that checkerboard patterns were used (Figure 2). A master checkerboard and tri-bar resolution target were photographed together. This was then photographed at varying camera focus settings. After the film was processed, the limiting resolutions were determined by trained photo interpreters, and specific photos were chosen to be used for stimuli. The photograph with the highest resolution was found first, and then frames with lower resolution were picked so that the resolution decreased by a constant factor of $\sqrt[6]{2}$, i.e., the lines/mm in the limiting resolution target decreased by 1.1225 in each successive photograph. This provided a linear psychophysical scale with respect to spatial frequency of the checkerboard target (Table 2). The contrast ratios of the frames were found by measuring the densities of the light and dark squares of the checkerboard. The space average luminances of the checkerboard portions of the frame were also measured using a Tektronix J16 Digital Photometer with a J6501 foot-candle head, yielding

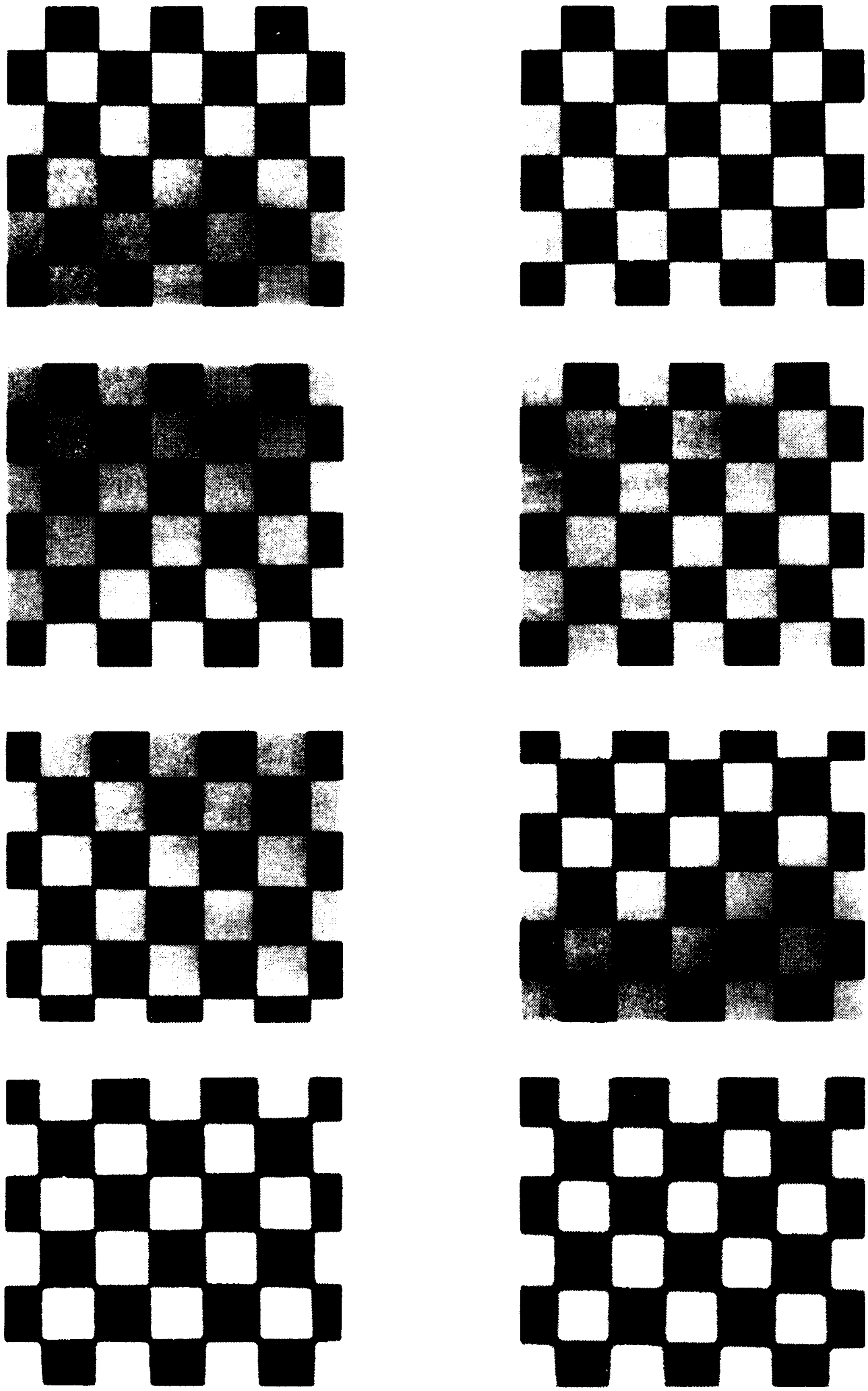


Figure 3. Checkerboard Patterns (Experiment 3)

TABLE 2

LIMITING RESOLUTION

Slide No.	Group Element No.	Lines/ MM	Contrast Ratio
1	2-3	58.77	2.2
2	2-5	32.98	2.2
3	1-6	18.51	2.3
4	1-1	10.39	2.3
5	0-2	5.83	2.3
6	-1-3	3.27	2.3
7	-2-4	1.84	2.2
8	-3-5	1.03	2.3

an average value of 22.5 ft. cd. (S.D. = 0.756). Both of these values were reasonably constant over all stimuli (Table 2).

d. Experiment Number 4

In this experiment, the stimulus materials consisted of a terrain photograph designed to simulate a downward view from an aircraft flying at about 14,000 feet. The terrain was a vegetative section of Ohio with roads and other landmarks (Figure 3).

Subjects saw a series of five progressively defocused slides projected through a Kodak RA-960 slide projector onto a smooth projection surface. Slides were systematically defocused in approximately one diopter steps. Special care was taken to ensure that the light transmission and the physical area of the terrain were equivalent among slides. Photometric measurement of the slides indicated an average light transmittance coefficient of 0.0426 with a 0.0365 to 0.0487 range. When illuminated with a 41-footlambert (Fℓ) source, the resulting mean

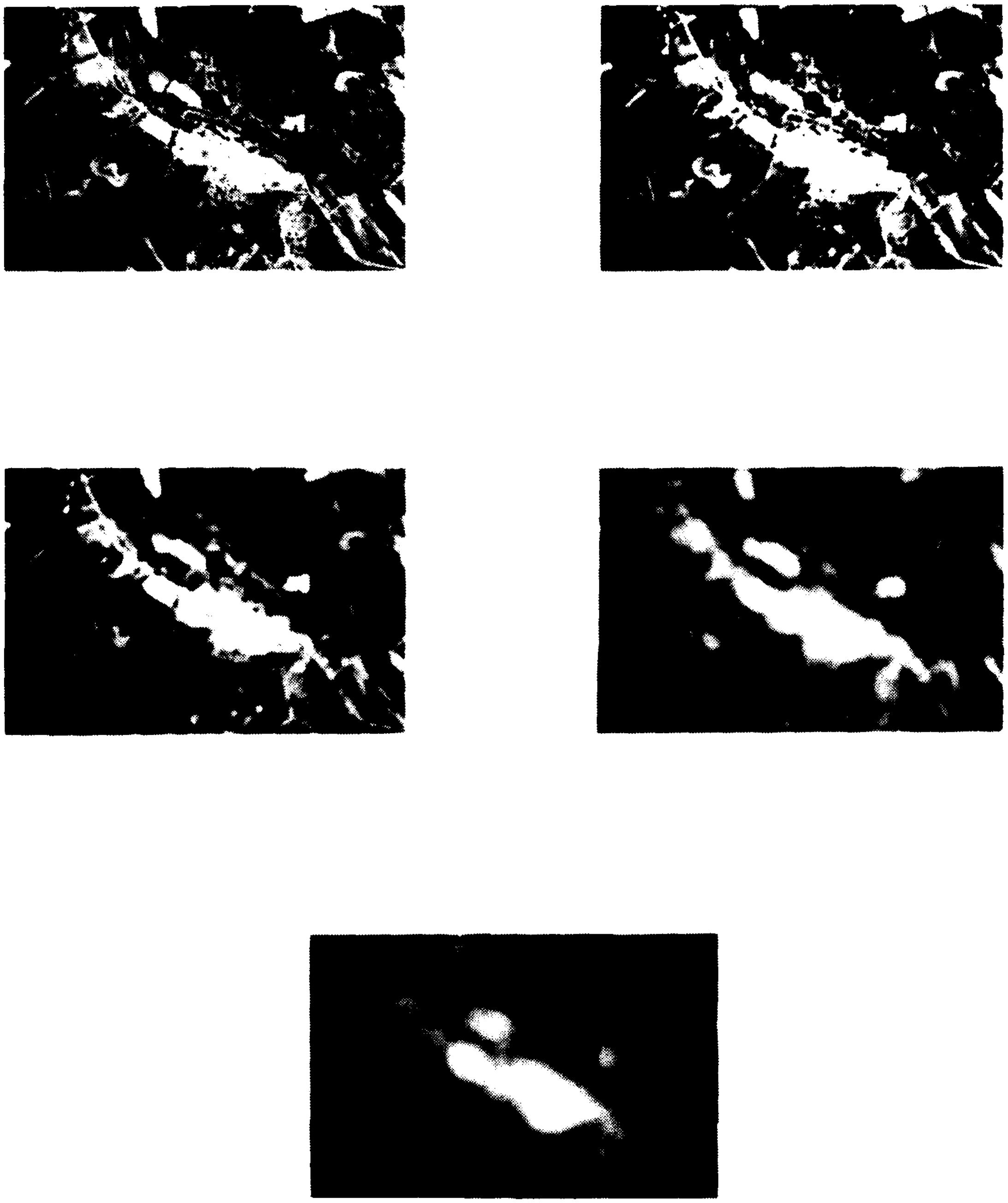


Figure 3. Terrain (Experiment 4)

luminosity for the projected image was 1.7 fl with a 1.5 to 2.0 fl range. The background luminance was approximately 0.02 fl. The projected image subtended visual angles of 11 degrees in height by 16 degrees in width at a viewing distance of 9 feet.

Two male and two female subjects were used in this experiment (age range 25 to 32 years). All subjects were familiar with evoked response procedures and had at least 20/20 vision. The subjects were instrumented with a bipolar occipital electrode montage with mastoids used for ground and reference. EEG amplification was 20K with a Grass P511 ac preamplifier. External filtering (Khronhite Model 3750) was done with settings of 0.01 to 50 Hz (24 db/octave roll off). Evoked responses were generated by flashing the projected image with light through a Model 225L4A0X5 Uniblitz shutter for 10 milliseconds every 850 milliseconds. For each trial, a Nicolet CA-1000 clinical averager collected thirty-five 300-millisecond epochs. Average evoked responses were charted on an X-Y plotter and analyzed manually.

At the beginning of each trial, the subjects were instructed to fixate upon a centrally located landmark of their own choosing. The slides were presented in the same order each time, but not in a regular sequence of focus (1,3,5,4,2). A short break was taken after the fourth slide due to instrumentation limitations. A typical session lasted about 15 minutes.

SECTION III

RESULTS

1. EXPERIMENT NUMBER 1

This experiment presented a single tri-bar target to the subject. The target was flickered at either 8 hz or at a frequency between 48 and 54 hz (referred to hereafter as "50 hz") and the steady-state evoked response was calculated. The evoked response amplitudes at both 8 hz and "50 hz" for each resolution level showed no pattern of change as a function of resolution. Analyses of variance were performed on the evoked response data for both the fundamental frequency and the first harmonic amplitudes of the 8-hz and "50-hz" trials. The ANOVA F-ratios can be seen in Table 3. Clearly, no significant effects due to resolution were seen in any of the four analyses. The amplitudes of the evoked responses varied greatly between subjects, a result commonly found in this measure. A strong effect was found due to contrast in both the fundamental and first harmonic at 8 hz stimulation.

To eliminate baseline variability between subjects, a non-parametric test was used. Friedman tests were carried out on the data ranked by resolution and by contrast separately. The results are presented in Tables 4 and 5.

Table 4 again confirms the lack of a consistently significant effect of resolution on the evoked response. This is true for both fundamental and harmonic at both stimulating frequencies. Table 5, however, indicates significant effects of contrast at all resolution levels for the 8-hz fundamental frequency.

To estimate the consistency of the contribution of contrast to the evoked response results, as opposed to focus level, an analysis was performed on the contrast values for each slide. The fundamental frequency amplitude of the evoked response to 8-hz stimulation was correlated with the measured contrast for each slide, using the Kendall coefficient of concordance (Siegel, 19XX). A Kendall value of 1.0 means that the evoked

TABLE 3

ANOVA TABLE FOR EXPERIMENT NUMBER 1

SOURCE	F STATISTICS			
	8 Hz FLICKER		50 Hz FLICKER	
	FUNDAMENTAL	FIRST HARMONIC	FUNDAMENTAL	FIRST HARMONIC
Resolution	1.72	1.55	0.40	0.42
Contrast	39.53**	10.68**	0.57	0.52
Subject	436.46**	1308.60**	72.61**	86.91**
Resolution * Contrast	1.38	1.26	1.12	1.14
Resolution * Subject	1.42*	1.27	0.71	0.97
Contrast * Subject	4.81**	4.97**	0.84	0.70

** - Significant at $\alpha = .01$

* - Significant at $\alpha = .05$

TABLE 4

FRIEDMAN RANK TESTS ON EVOKED RESPONSES TO VARIOUS RESOLUTIONS

RESOLUTION LEVELS	FRIEDMAN STATISTIC			
	8 Hz FLICKER		50 Hz FLICKER	
	FUNDAMENTAL	FIRST HARMONIC	FUNDAMENTAL	FIRST HARMONIC
1	11.725	6.308	6.733	4.733
2	16.850 *	5.750	4.400	4.267
3	1.442	7.875	3.300	4.933
4	10.892	8.600	2.533	3.567
5	8.992	8.767	16.500 ***	11.900

* Significant at .10 level
*** Significant at .025 level

TABLE 5

FRIEDMAN RANK TESTS ON EVOKED RESPONSES TO DIFFERENT CONTRAST RATIOS

CONTRAST RATIO LEVELS	FRIEDMAN STATISTIC			
	8 Hz FLICKER		50 Hz FLICKER	
	FUNDAMENTAL	FIRST HARMONIC	FUNDAMENTAL	FIRST HARMONIC
1	12.72***	3.68	0.88	1.36
2	18.08****	6.88	1.76	3.38
3	10.88**	6.80	6.56	5.76
4	17.84****	14.32*	5.76	10.10**
5	16.40****	4.46	2.48	1.12
6	12.54***	3.62	5.20	1.52
7	8.08*	5.44	4.64	5.84
8	15.28****	5.36	2.24	5.12

*Significant at .10 ***Significant at .025
**Significant at .05 ****Significant at .005

response to each contrast level had the same relative rank for all subjects. Overall, the Kendall coefficient in this analysis was 0.298 ($p < .001$) indicating a low but substantial dependence of the 8-hz evoked response on contrast. Kendall coefficients for the trained photo interpreters were essentially equal to the untrained subjects. However, the evoked response rankings of one subject in the trained group were consistently different than the others. When this subject's data are removed from the trained group's data, the Kendall coefficient goes up to 0.670. This means that, but for one subject, the trained group would have shown much more consistent relationships between evoked response and contrast than the untrained group. The overall relationship between evoked response and contrast in each subject is shown graphically in Figure 4. From this, it is clear that a strong relationship holds. In addition, the clearly atypical result from one subject is easily seen.

A possible cause of the failure to find a significant relationship between evoked response and resolution in the first experiment was the absence of enough final detail in the images. Only one group of bars was shown to the subjects, and this group had a 2° angle of view. Although the edges contained some high frequency information, no small details were shown to the subjects.

Another possible cause for the lack of a resolution effect is that the tri-bar stimulus used had a mask surrounding the degraded image. This mask was very close to the focus of the projector, so the edges of the mask were always presented to the subjects in good focus. Thus, even on the slides of low resolution, there were areas of sharp edges and therefore high spatial frequency content.

Finally, the significant contrast effects demonstrated in the first experiment constituted a confounding factor in probing for resolution effects.

2. EXPERIMENT NUMBER 2

The second experiment replicated the first with respect to the 8-hz steady-state stimulation. Single tri-bar and whole tri-bar resolution targets were used, using only one contrast level of each slide. In

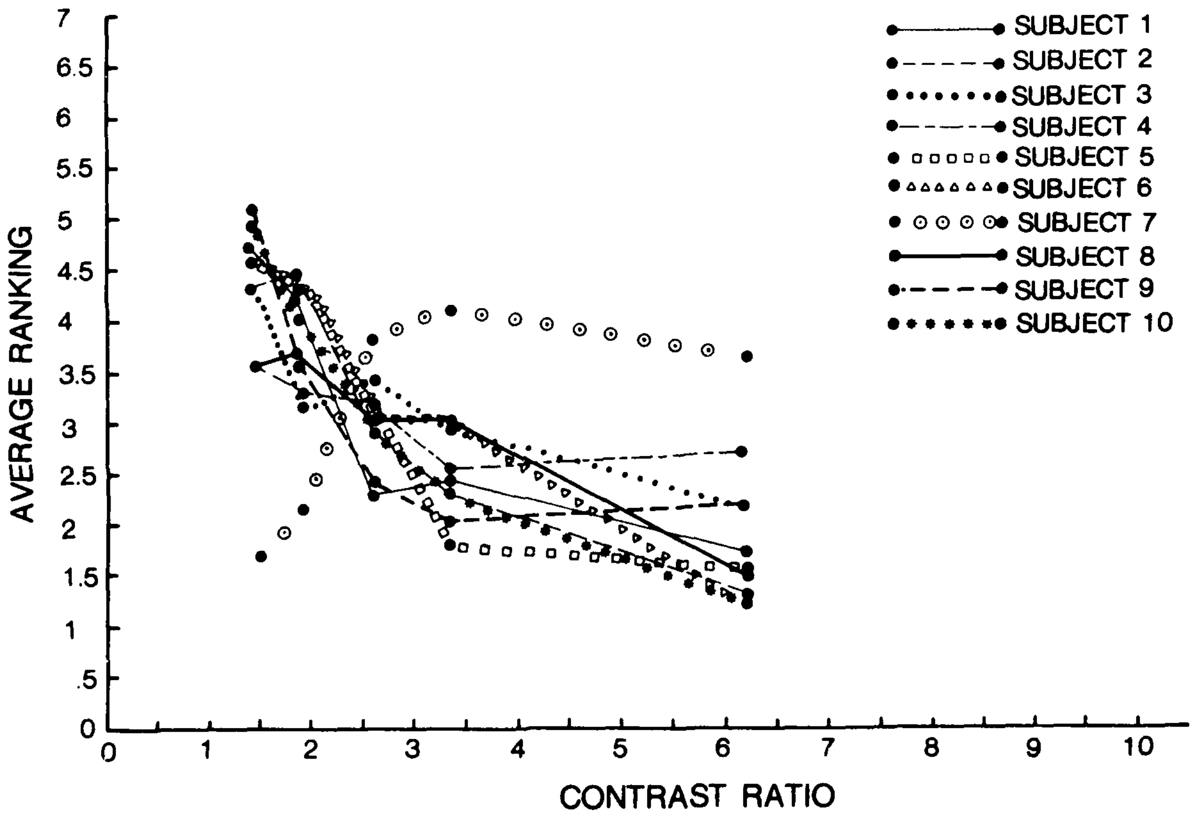


Figure 4. Evoked Potential Responses Contrast Ranking, Exp. 1

addition, in order to look at the transient evoked response, slides were also presented in discrete, 1-second-long displays.

To control for the possible confounding caused by the sharp edges of the mask in experiment one, the mask in this experiment was placed well away from the projector focus. In this way, the edges were always out of focus and included only very low spatial frequency content.

3. STEADY-STATE RESPONSES

The amplitudes of the 8-hz fundamental and first harmonic evoked response were analyzed for both single tri-bar and whole resolution target. Analyses of variance and chi-square analyses confirmed that there were no significant differences or trends as a function of focus level.

Inspection of the actual evoked response wave forms revealed, however, an interesting tendency. Figure 5 shows three representative waveforms obtained from slides at three focus levels. While the major peak latencies are clearly similar and that averaged amplitudes would be the same, there are clear patterns of large and small amplitude peaks that are different as a function of focus. Put differently, these three "8 hz" waveforms appear to be composed primarily of an 8-hz fundamental and a 16-hz harmonic which appear to be shifting phase relationships indpendently. Each of the waveforms seen in Figure 5 can be electronically reconstructed with great fidelity from 8- and 16-hz sine waves shifted slightly with respect to each other.

In view of this, the 8- and 16-hz phase delay to 8-hz stimulation were analyzed for both single tri-bar and whole resolution targets. These phase relationships were obtained by re-processing the raw data directly through the Nicolet FFT analyzer (see procedure section) yielding phase relationships relative to the input signal. These data were then transformed by adding 360° (or 720°) to account for the fact that the actual phase may have been one or two full cycles removed from the measured phases. This transformation was relatively straightforward since plots of the measured phase angles clearly showed the points where

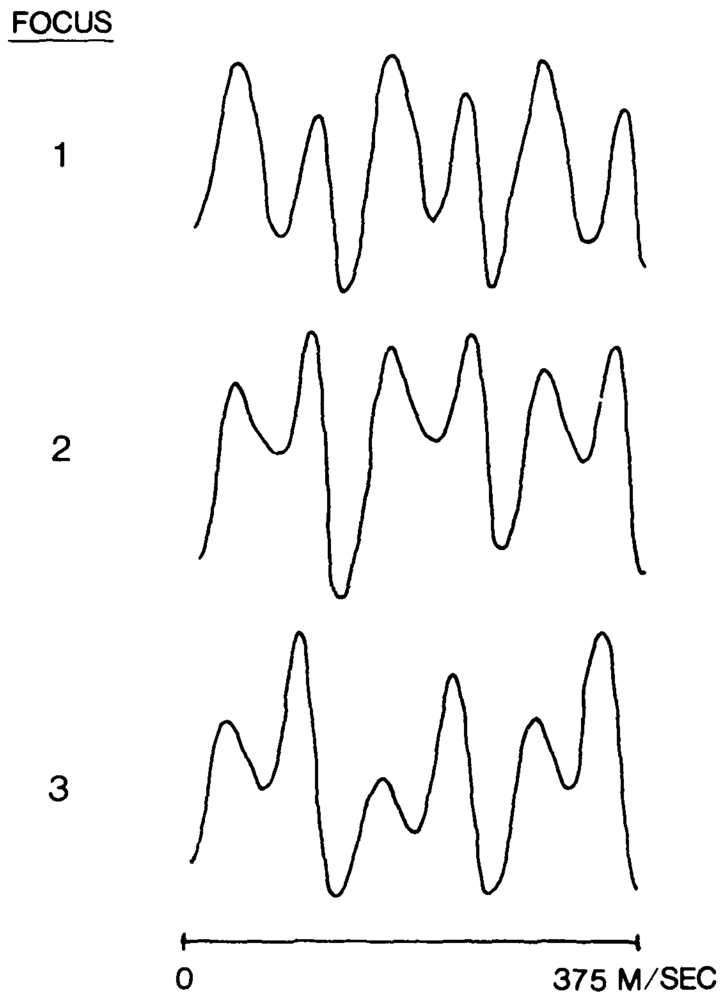


Figure 5. 8-Hz Steady-State VER

whole cycles were exceeded. To further reduce the internal scaling assumptions necessary for parametric analyses, the data were then rank-ordered so that non-parametric statistics could be used.

Amplitude analyses on these re-processed data again failed to reveal significant effects of focus for either 8- or 16-hz amplitude (Friedman test, Chi-square for single tri-bar slides = 5.6 for 8 hz and 3.1 for 16 hz, both non-significant; for whole resolution targets, 1.7 for 8 hz and 7.9 for 16 hz, both non-significant). However, the phase relationships revealed a significant effect of focus on the 8-hz phase for the single tri-bar target (Chi-square = 25.5, $p < .01$). No significant effect of focus was found for 16-hz activity to the single tri-bar, nor to either 8- or 16-hz activity to the whole resolution target (Chi-square = 1.91 for 8 hz and 11.6 for 16 hz, both non-significant).

Figure 6 shows these relationships graphically for the single tri-bar target. It is clear that the 8 hz activity to the single tri-bar shows a consistent decrease in phase angle going from sharp to poor focus. None of the other measures shows this consistency. These data therefore confirm the initial impression that phase relationships may be significantly altered as a function of focus level, at least for relatively simple tri-bar targets. The effects apparently occur at the stimulating ("fundamental") frequency, with higher harmonic frequencies not showing phase shifts as a function of focus.

4. TRANSIENT EVOKED RESPONSES

Transient evoked responses were obtained to both single tri-bar and whole resolution targets presented to the subject for 1 second. Each focus level was presented a total of 32 times (with "catch trials") to generate an ensemble average. Representative examples of the responses are shown in Figure 7.

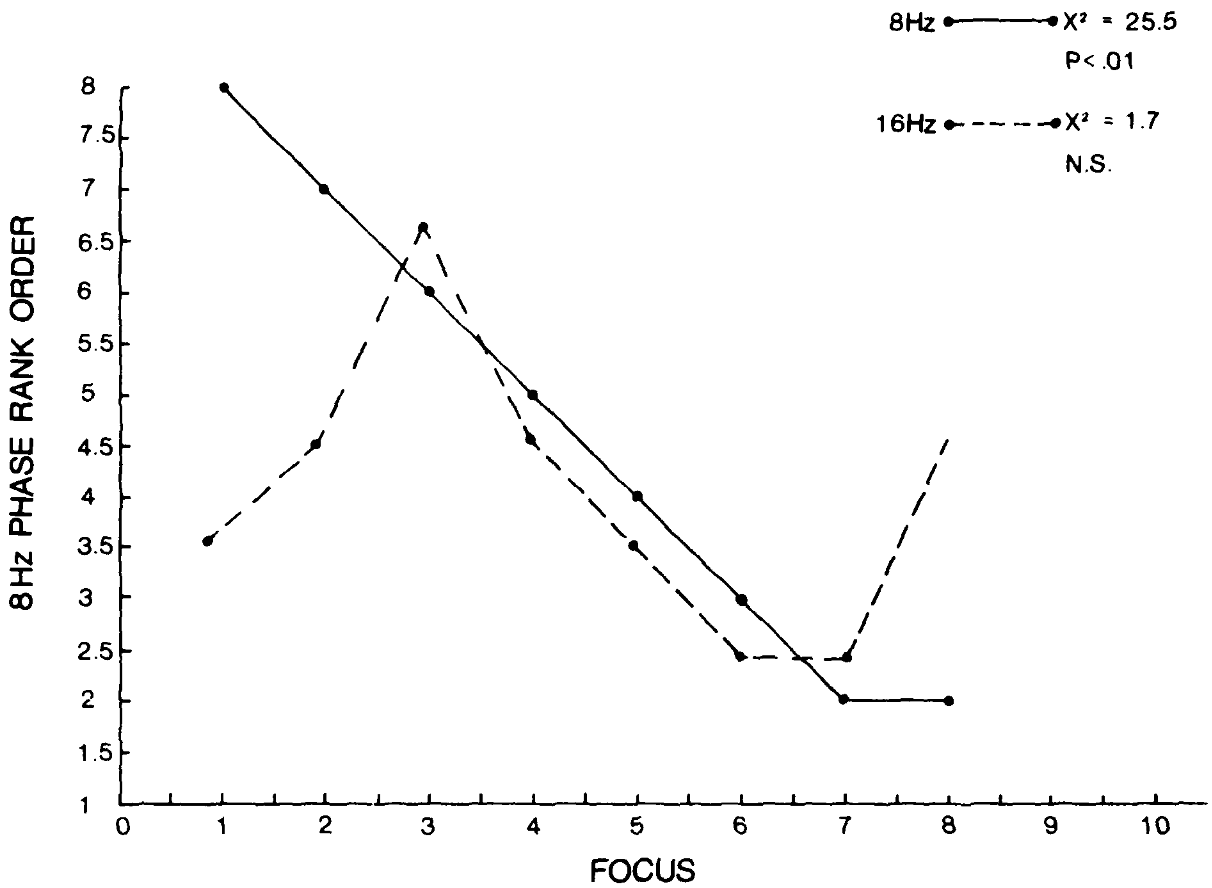


Figure 6. 8-Hz and 16-Hz Phase by Focus Partial Slides

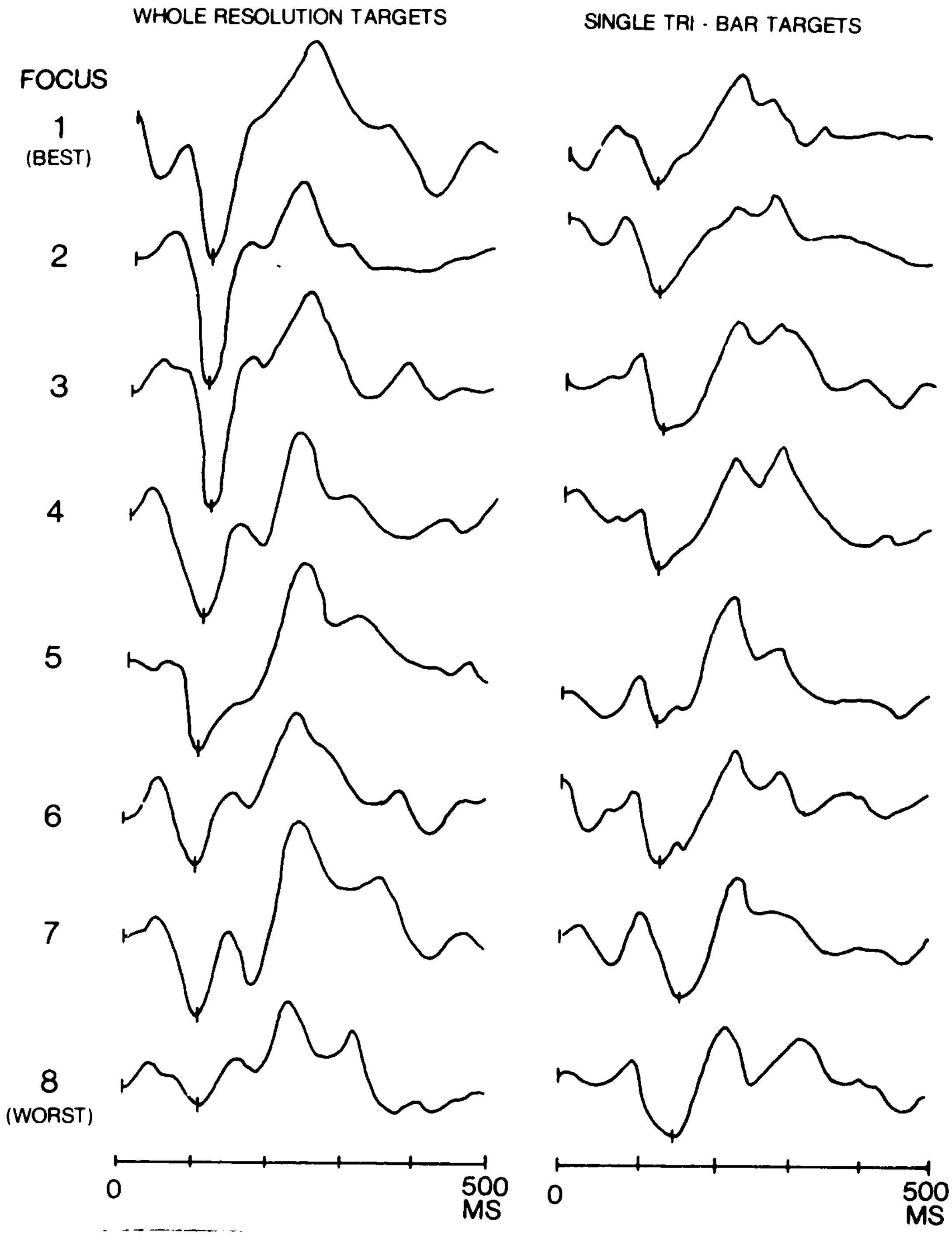


Figure 7. Transient Evoked Potentials to Targets at Various Focus Levels (Positive Up)

The single peak which has been most frequently identified as sensitive to changes in focus level of targets is a negative going event between 95 and 110 msec after the stimulus is presented (Harter and White, 1968). This peak was therefore measured for all subjects and their rank orders were analyzed by Friedman non-parametric tests. For single tri-bar slides, this peak did not appear sensitive to focus (x^2 = 6.0, 7 d.f., not significant). However, for the whole resolution target, this peak showed a marginally significant decrease in amplitude with decreasing focus (x^2 = 13.6, 7 d.f., $p < .07$). Although only marginally significant statistically, this relationship was rather clear-cut and was frequently visible in the single subject's data. Figure 8 presents the combined ranks for both the single tri-bar and whole resolution targets. While the lack of an orderly relationship in the single tri-bar response is clear, the overall change in this peak for the whole resolution target is also striking. Apparently, the negative activity at 90-110 msec is dependent on multiple sharp edges and is a reasonably sensitive indication of the sharpness of these edges.

5. EXPERIMENT NUMBER 3

This experiment again probed the steady-state evoked response, using stimuli which could be controlled precisely and which would be expected to maximize any effects due to focus. Checkerboard stimuli were counter-phase flickered (i.e., black checks alternated with white) at 8 hz and steady-state activity at 8 and 16 hz were analyzed.

Both amplitude and phase data for this experiment showed no consistent relationship to focus level. Averaged ranks (over subjects and trials) for both amplitude and phase are shown in Figures 9 and 10. Although there might appear to be a curvilinear relationship between 8-hz amplitude and focus, this was not statistically demonstrable. In addition, inspection of raw data revealed an extremely small variation in absolute terms between the best and worst focus level on this measure.

Further inspection of raw data revealed poor consistency even within a subject on both amplitude and phase measures as a function of focus. In other words, even within subjects the same focus did not always

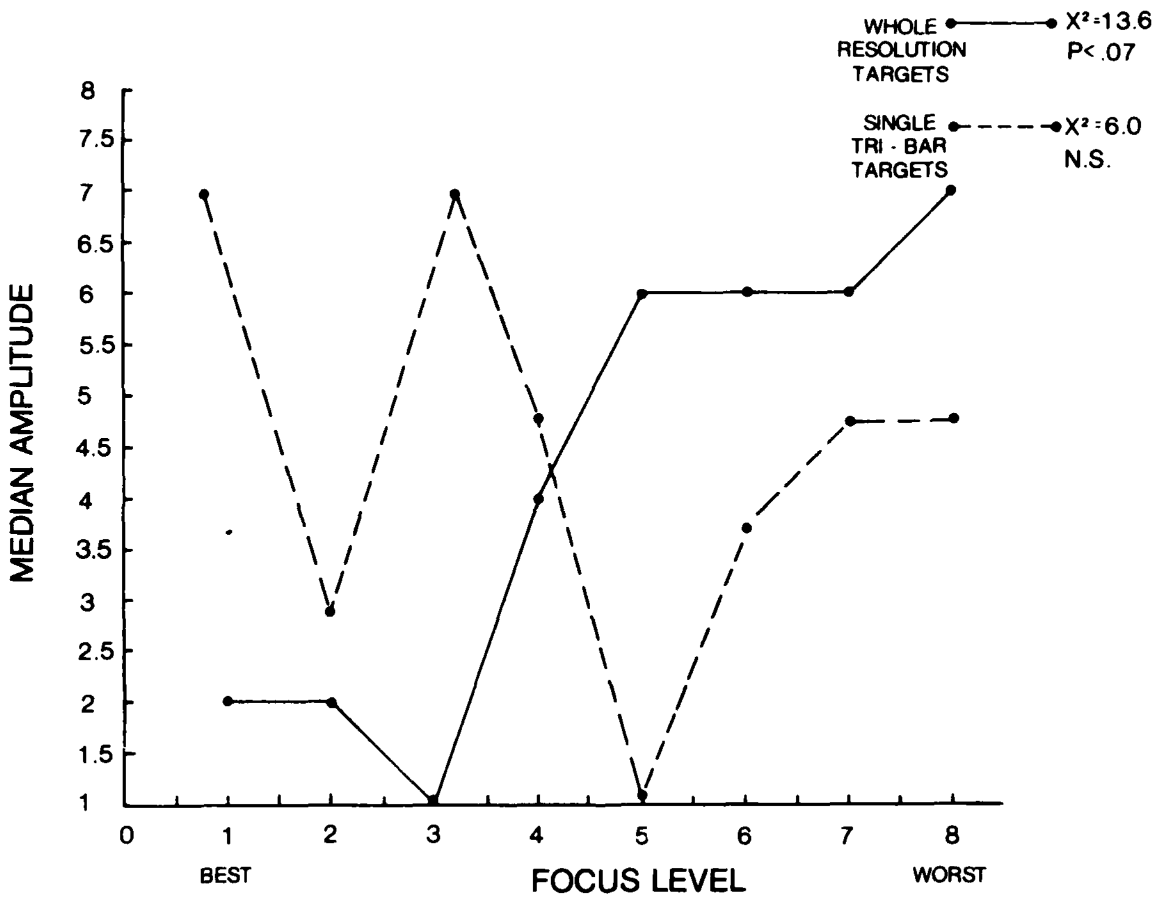


Figure 8. Amplitude of 90 - 110 msec Negative Peak in Transient Evoked Response as a Function of Focus

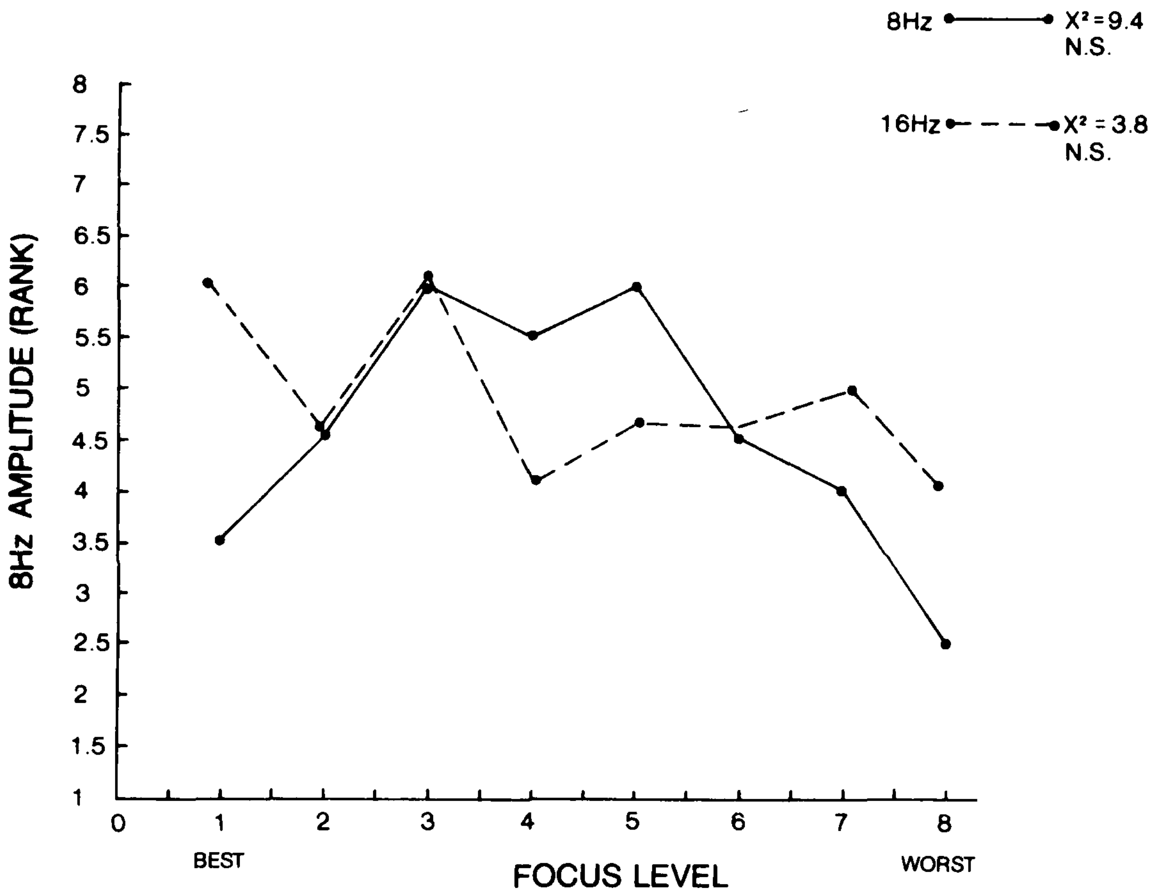


Figure 9. 8-Hz and 16-Hz Amplitude of Steady State Evoked Responses as a Function of Checker Board Focus

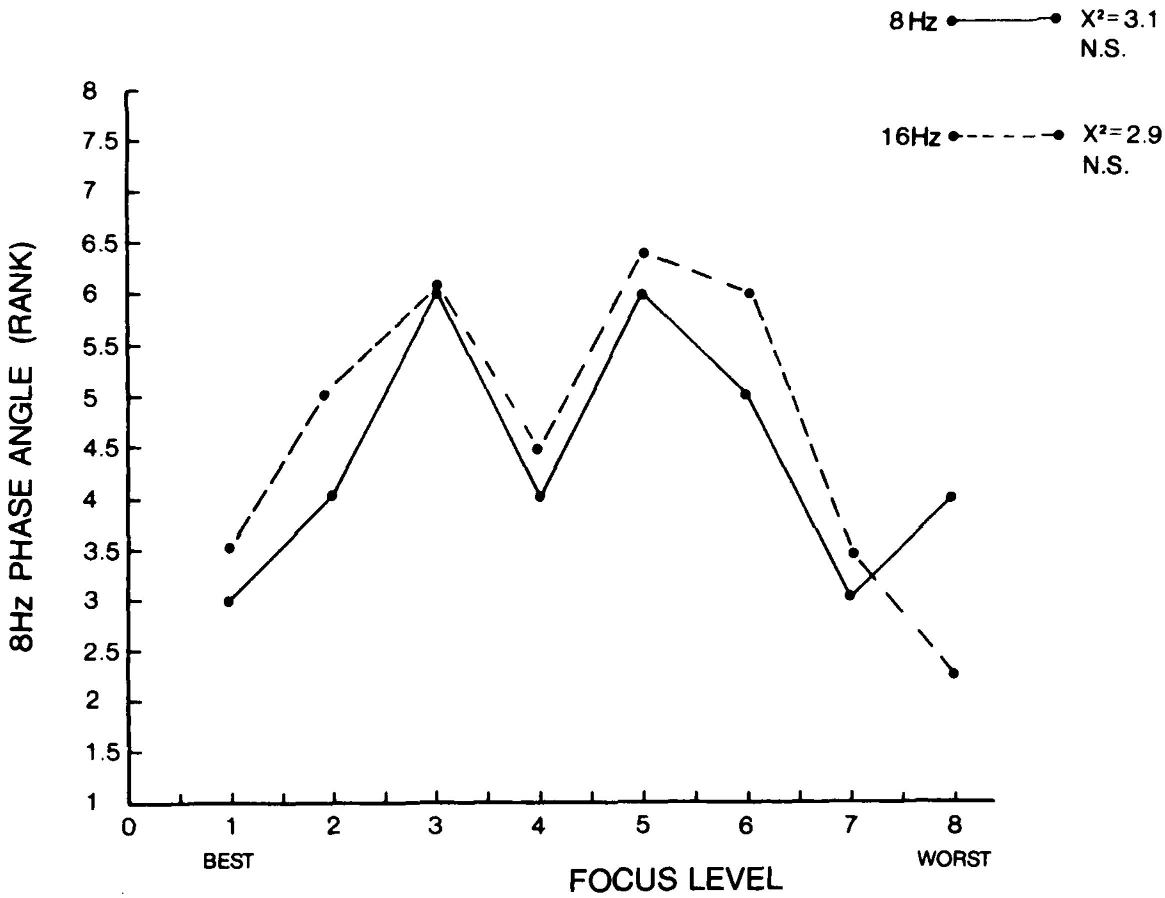


Figure 10. 8-Hz and 16-Hz Phase Angles of Steady State Evoked Responses as a Function of Checker Board Focus

produce the same steady-state response, either absolutely or relatively. To test this, Kendall coefficients of concordance were calculated for all subjects over sessions and conditions. These revealed generally poor repeatability, with only two of the eight subjects showing consistent response over trials. Clearly, the procedures used in this experiment failed to demonstrate any reliability of the steady-state evoked response as a measure of focus.

6. EXPERIMENT NUMBER 4

This experiment attempted to provide the most "realistic" conditions of any used in the present series and to capitalize on the results obtained in the first three experiments. If complex imagery was used, the transient evoked response appeared to provide the most sensitive indicator of focus. Therefore, a terrain photograph was systematically de-focused, and the transient response was obtained.

Results obtained from each of the four subjects are shown in Figure 11. Inspection of all major peaks revealed an event between 120 and 170 msec after stimulus presentation which appeared to vary systematically with focus, in both amplitude and latency, for all subjects.

To probe this event more fully, its amplitude was measured relative to the average amplitude of that evoked response for the first 30 msec after stimulus presentation. This technique tends to reduce variability and is comparable to the measurement of peak to trough amplitudes with some significant advantages.

Results of the analysis for amplitude of this peak are presented in Figure 12. The mean values for each focus level are monotonically related to focus over the range tested. To determine if these trends were consistent enough over subjects to demonstrate statistical significance, the amplitudes were ranked and analyzed by Friedman test. A significant Chi-square (15.6, d.f. = 4, $p < .01$) was obtained for these data. Thus, in general agreement with the transient response results in experiment two, an early peak appears to index focus level reliably over subjects in complex imagery.

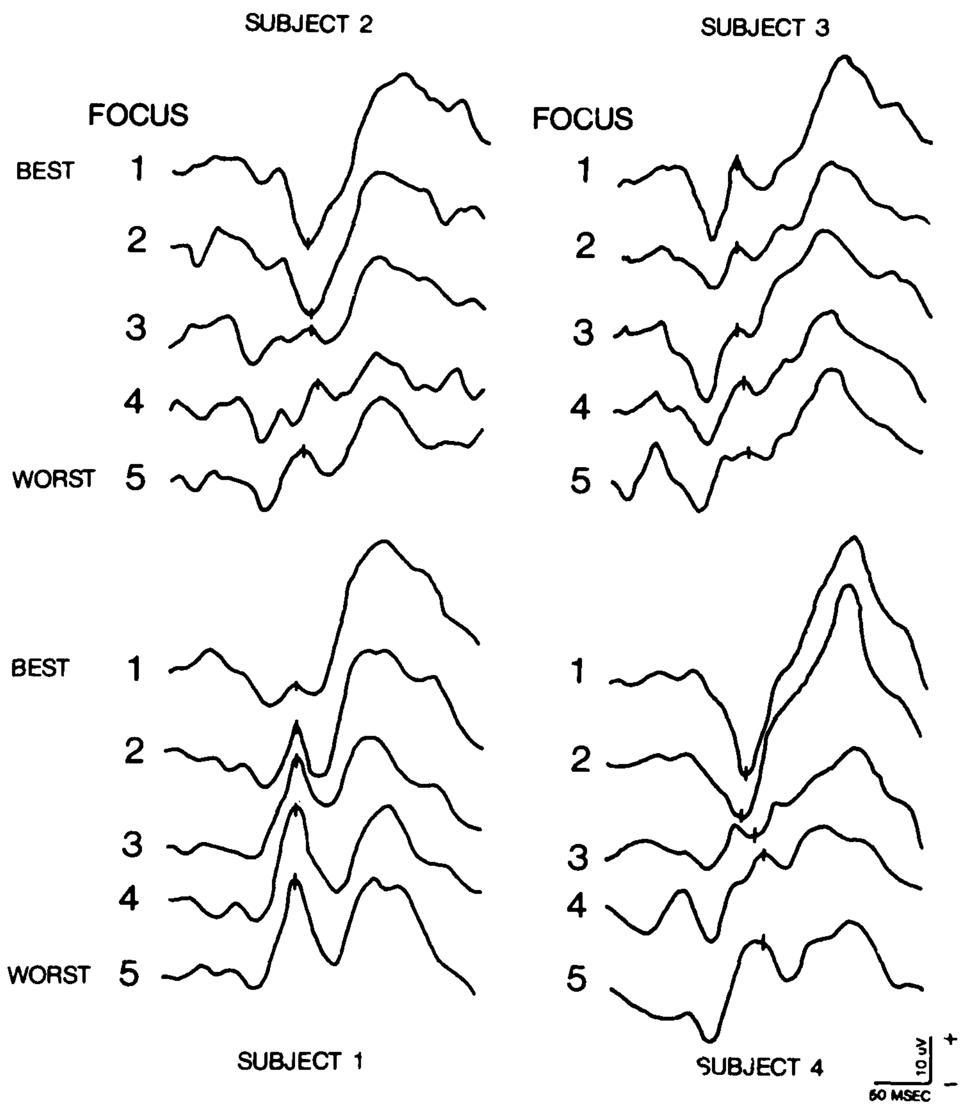


Figure 11. Transient Evoked Responses to Terrain Photograph De-Focused in One-Diopter Steps

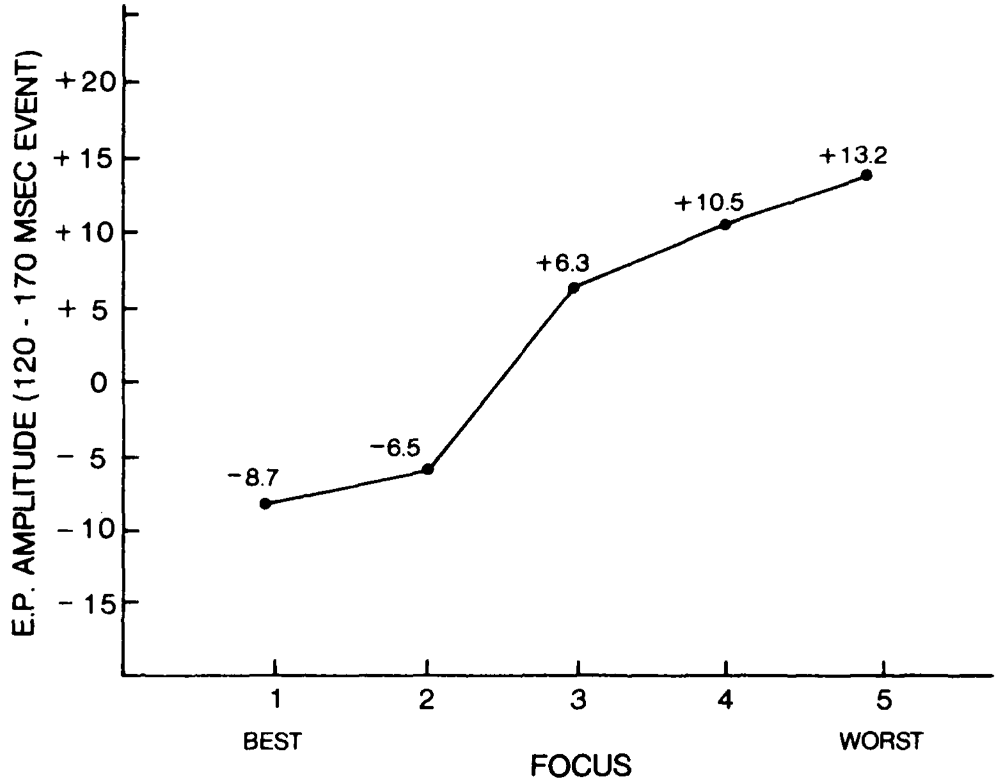


Figure 12. Transient Evoked Response Amplitude to Terrain Imagery as a Function of Focus (120 - 170 msec Event)

Latency of this peak was also analyzed as a function of focus, and these results are shown in Figure 13. Again, a monotonic relationship is seen, with the sharpest focus producing the lowest latency. When these data were subjected to non-parametric analysis, however, the Friedman chi-square was only marginally significant ($x^2 = 8.55$, d.f. = 4, $p < .07$). This was due to occasional reversals within subjects in the rank order of their responses, while their general pattern, as well as the averaged rank, followed the overall trend.

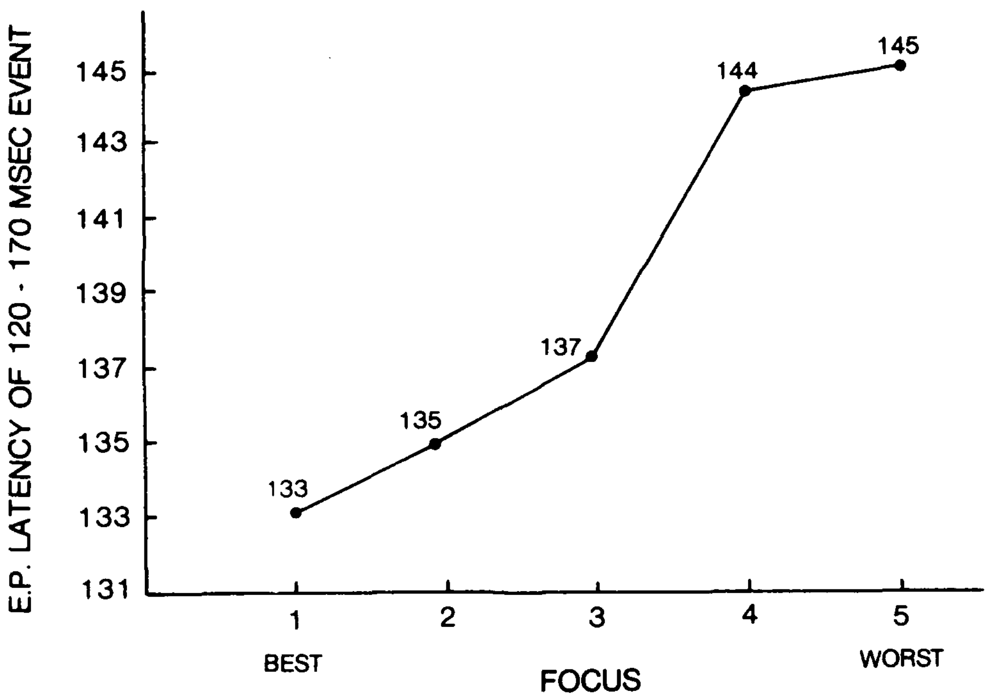


Figure 13. Transient Evoked Response Latency to Terrain Imagery as a Function of Focus (120 - 170 msec Event)

SECTION IV

DISCUSSION

The goal of this series of experiments was to begin the transition of a laboratory technology to a specific application. A number of procedures involving the generation of cortical evoked responses were tested for their utility and sensitivity in indexing the focus level of various kinds of targets. In line with the basic nature of the investigation, laboratory controls attempted to isolate the factors, within each type of stimulus, that were contributing to any effects observed. The four studies investigated the steady-state and transient evoked responses to presentation of standard Air Force tri-bar photographs, checkerboard patterns, and complex real imagery. The first experiment failed to find sensitivity of either the low frequency (8 hz) or high frequency (about 50 hz) steady-state evoked response to differences in the focus level of a single Air Force tri-bar grating. These results were confounded, however, by a highly significant effect of contrast level for the gratings, as well as the fact that some high frequency information was presented to the subject along with the defocused images. This experiment raised the question whether a large number of edges would be required in the stimulus image in order for the steady-state evoked response to be useful as an index of focus.

The significant effects of contrast on the steady-state evoked response are interesting in themselves. With the exception of one atypical subject, there was a very good relationship between the steady-state amplitude and contrast ratios ranging from 1.5 to 13. This relationship is, of course, significant in its own right and could be useful in many contexts, since contrast ultimately contributes to the identification of images embedded in noise. However, since contrast was not the major focus of the present series of experiments, this avenue of potential research was not pursued.

The second experiment attempted to add additional controls for contrast, and also excluded of high spatial frequency information. Again, the amplitude of the fundamental steady-state evoked response frequency failed to discriminate focus level of either single tri-bars or whole resolution targets. However, further analysis revealed that the phase of the fundamental frequency was indeed affected by the resolution of the target.

This result is somewhat confusing, since the first harmonic of the stimulation frequency was not similarly affected by target focus. Such a dissociation between fundamental and harmonic is difficult to interpret for a system which is presumed to be linear. However, Regan (1975) has shown such a dissociation between the stimulating frequency response and its higher harmonic with respect to color, and has suggested that the steady-state evoked response to medium-high frequency chromatic stimulation may contain distinct elements, perhaps related to different visual information traveling along parallel channels very early in the visual system. While this speculation cannot be confirmed at this point, it could help explain the fact that the 8-hertz phase may be sensitive to the spatial frequency information in a stimulus, while its harmonic is not.

The situation is somewhat further confounded by the fact that the phase effect was seen only for the single tri-bar target. Although the whole resolution target showed a tendency in the same direction, the data were not statistically significant. This result suggests that the fundamental phase change generated by defocusing an image may be most observable when the image contains few edges. Thus, the response seen in the phase shift could be a very "primitive" function of the visual system which operates when other complex factors are minimized. In any case, these two experiments indicate that the steady-state evoked response should not be considered as a likely candidate for utilization in the kinds of application envisioned for the present series of studies. The third experiment further confirmed this tentative conclusion, failing to find significant effects of focus on a well controlled checkerboard stimulus. This is not to say that the steady-state evoked response may not be useful in other contexts or even as a measure of focus if a different set of procedures are used. However, as used in the present series of experiments, this type of steady-state technique does not appear to represent a profitable measure of image resolution.

On the other hand, the second half of the second experiment utilized the transient evoked response to the same tri-bar stimuli and found a marginally significant decrease in amplitude as focus became worse. This effect was found in a peak which previously had been reported to be sensitive to target focus, and therefore confirms the observation of Harter and White (1968). Further, although marginally significant from a statistical viewpoint, the effect was clearly observable in several subject's records, and appeared to be a robust phenomenon. The value of the transient evoked response was confirmed in the fourth experiment where, using complex imagery, an evoked response event was significantly related to focus level, both in amplitude and latency. This event was slightly later than that seen in the second experiment, but this is understandable in view of the complexity of the image. Again, decreasing focus resulted in a reduction in the negativity of the event and, in agreement with the data of Harter and White (1968), showed the event becoming positive with extremely poor focus.

Note that in the fourth experiment, the imagery was significantly degraded (approximately 1 diopter between images). Such data cannot, therefore, be used to assess the sensitivity of evoked response to the focus of complex imagery. In fact, the overall impression is that, as used nere, the transient evoked response is a reliable but not extremely sensitive index of image focus.

In general, the present series of experiments tends to confirm the fact that the cortical evoked response, particularly as generated by transient presentation of stimuli, is a reliable index of image focus. Significantly, this was found both for relatively simple (tri-bar) imagery and for extremely complex "real-world" imagery. Having established this basic validity and applicability to complex imagery, it should be possible to probe for ways to increase the sensitivity of the measure. Future studies should conentrate on the transient evoked response techniques tested here (while not ignoring different techniques for generating the steady-state evoked response which may also prove valid).

With respect to the transient evoked response, the utilization of single-event evoked response measurements may prove to be a more sensitive measure than the ensemble average techniques utilized in the present studies. In averaging, many events obviously are combined. Pre-filtering of the EEG to determine such things as operator readiness, blinks, muscle tension, and other factors which may "smear" the overall average could contribute sensitivity to the measure. Specific "probe" stimuli that are known to give extremely sensitive responses to image focus could be generated, and these could be incorporated into the operational contexts. The present series of studies have firmly established the potential applicability of this technique to operational situations. They have not, however, carried the technology to the point where it can be presently incorporated. With additional careful, systematic exploration and exploitation, the cortical evoked response procedure may prove to be an operationally useful measure of photographic image quality.

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