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Original Article

A DIGITAL FAST SWEEP TECHNIQUE FOR STUDYING STEADY-STATE VISUAL EVOKED POTENTIALS

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Abstract—*A digital fast sweep technique for recording and analyzing steady-state visual evoked potentials is described The present system is based on a DEC LSI-11/23 computer. Most of the function is put into software, so that only minimal additional hardware is needed The computer handles the generation of one-dimensional temporally modulated stimulus patterns, data acquisition, and data analysis, and provides a friendly user-interface Besides discussing the structure of a measuring system, this report also treats principles of digital stimulus generation and data acquisition. The main advantage of such a computer-based system is that it combines the versatility of a general purpose computer with the reliability and speed of digitally implemented methodologies The availability of such a system allows the more general clinical use of steady-state evoked potentials for studying spatial vision.*

Keywords—Computer, Fourier analysis, Gratings, Pattern vision, Sampling, Software, Steady state, Sweep technique, Visual evoked potential, VEP

INTRODUCTION

The electrical activity of the brain is accompanied by potential differences at the scalp which can be registered by the electroencephalogram (EEG). Caton, the inventor of this method, noted as early as 1875 that sensory events lead to variations in the EEG, yet since these "evoked potentials" (EP) are of small amplitude (0.1 to 10 μV) they are masked by the stronger spontaneous EEG (10 to 100 μV). With the availability of electronic averaging computers in the early sixties, evoked potentials could be routinely recorded and soon found clinical applications. Among these, the visual evoked potential (VEP) plays an important role in neurology, specifically for the diagnosis of multiple sclerosis.

Several filtering methods can be used to separate the EP from background EEG noise, the most commonly employed method being the averaging of EEG traces with the stimulus onset time serving as a synchronizing trigger. In the case of the VEP, 100 or more stimuli are presented at a rate of ca. 2/sec, leaving enough time for the response to decay before the next stimulus is presented. Flashes of light have commonly been used as stimuli but nowadays patterned stimuli are used increasingly. Opposed to these transient VEPs, the use of steady-state VEPs has been proposed[16–18 24] mainly for their higher recording speed. The stimulus is presented continuously and modulated in pattern con-

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trast at a rate which is much higher than the presentation rate of transient VEPs. The evoked response does not decay but reaches a steady state, oscillating at the frequency of the stimulation rate or a multiple thereof.

A relationship between evoked potentials and conscious perception has been demonstrated by Keidel[9] who showed that thresholds of auditory EPs correspond to psychophysical detection thresholds. Later, Campbell & Maffei[6] obtained a similar result for the steady-state VEP elicited by phase-alternating sine-wave gratings (i.e., gratings with sinusoidal intensity profile where black and white bars alternate periodically). The relationship between VEP amplitude thresholds and the psychophysical contrast sensitivity function has been extended to cats[2 7] where behavioral estimates and results from single unit recordings[10] are also closely correlated. This progress of physiological research suggests that the range of clinical VEP applications might be extended to the analysis of visual dysfunction[1 5 17 19] as well as to monitoring early visual development (for a review see Dobson & Teller[8]).

The use of steady-state VEPs appears particularly promising due to their higher recording speed: VEP recording for a high number of stimulus parameters, as for example required by the regression technique for determining thresholds described by Campbell & Maffei, requires long recording times which are a problem in a clinical setting. Recording time may be further reduced by the use of a sweep technique[15,25] which is well known from electrical engineering. In this method, an independent variable, such as contrast, is changed fairly rapidly ("swept") and the EP response is registered. In this way, a whole functional relationship is obtained instead of individual measured points.

Despite these highly promising developments, the steady-state VEP (SSVEP) has not yet found widespread use in neuro-ophthalmology. We feel that this is mainly due to two reasons. First, SSVEPs have usually been recorded by means of laboratory equipment which is not easily adapted and duplicated for clinical application (for a review of laboratory techniques of VEP stimulus generation see Arden et al.[2]). Second, and as a consequence of the above, there is no broader data base available with reference to which clinical findings could be evaluated. This prompted us to develop a digital fast sweep technique for recording and analyzing SSVEPs. The main advantage of such a system is that it combines the versatility of a general purpose computer system with the reliability and speed of digitally implemented methods.

Another factor hampering the clinical application of VEP methods is that transient VEPs do not have a reliable response amplitude. As a consequence of this, amplitude data have a reputation of being unsuitable for diagnostic purposes. However, nonevent-related amplitude variations probably occur relatively slowly. Rapid measurement can therefore improve reliability. The present system combines the aforementioned techniques for high recording speed—(recording of steady-state potentials and the use of a digital sweep technique) with computer control of the whole experimental session. The latter avoids the tedious manual variations of parameters, the checking for accuracy, etc. The reliability of the data also depends on the availability of a well-designed ("user-friendly") user interface. Furthermore, an automatic report facility ensures that result files carry all the information on experimental conditions which is necessary for the subsequent interpretation of the data.

The SSVEP measuring system that we describe is based on Digital Equipment's LSI-11/23 computer. Most of the function is put into software, so that only minimal additional hardware is needed. The computer handles stimulus generation, data acquisition and data analysis. Unlike the authors of previous studies, we have used a fully digital implementation allowing for excellent accuracy and reproducibility of experimental conditions. (Norcia & Tyler have recently developed a system similar to ours which is based on an Apple-II microcomputer.[13]) Another advantage of using a general-purpose computer, as compared to dedicated digital hardware, is the easy integration into a larger laboratory system. This allows convenient further data analysis. Last, but not least, by using a general-purpose computer system, simple and reliable user operation is possible. The importance of this for clinical practice is obvious.

The present system is designed to fill a gap between commercially available EP recording systems and specialized laboratory systems. It is preprogrammed with a choice of stimuli and measurement procedures. It also provides an open architecture which can be tailored by a programmer to fit the needs of an individual research project. This report describes the system and discusses its design principles in sufficient detail to provide a basis for other designs.

GENERAL STRUCTURE OF THE SYSTEM

The range of the application and the performance of the whole system are largely predetermined by two basic design decisions: The choice of the computer and the question of whether stimulus generation is done by the main computer or external hardware. There are several good stimulus generation units available, both for one-dimensional gratings (e.g., Keck & Fritsch Ass.) or two-dimensional patterns (e.g., Innisfree, Ltd.). These units are programmable; the stimuli can be prepared on the main computer and "down-loaded" onto the stimulus unit. We have chosen to have the main computer generate the stimuli, however. The primary advantage of this was that minimal additional hardware was needed. However, since the price relationships between the system's components have changed dramatically since, this decision would have to be reconsidered for a new design. For example, while computer hardware and raster technology display units now cost a fraction of their cost some years ago, the cost of XYZ display units has increased. The price we had to pay for the saving of stimulus generation hardware was that we had to develop special complicated software for the real-time parts of the application. Stimulus generation by the main computer is restricted by the processor speed to one-dimensional, temporally modulated stimuli. Separate pattern generation programs prepare the stimuli at the beginning of the data acquisition session and store them on floppy disk or in main memory. The buffers are copied into the working memory for presentation where they are scanned at high temporal rates, and the data are sent to a digital-to-analog converter (D/A) driving the z-input of a CRT display. X- and y-deflections for generating frames are performed by external generators with each frame being triggered by the computer. Even for moderate display frame rates and spatial resolution, this scanning method poses tight time constraints on the system; the time-critical parts of the software have to be written in assembly language for optimum speed.

The system is equipped with 256K bytes memory and two 8″ double density floppy disk drives and runs the RT-11 (V4) operating system. While 64K bytes would suffice with the present software, the larger memory can be profitably used to hold the stimuli, thus greatly improving the system's performance. One floppy is used as the system and program disk while the other holds experimental data. Laboratory interfaces are a (16-channel) 12-bit A/D, a (four-channel) 12-bit D/A, a 16-bit digital I/O board, and a programmable clock (all by Data Translation). Peripherals are a Princeton type PAR 113 physiological preamplifier, a Rockland model 452 analog filter for anti-aliasing, and Tektronix series 500 triangle- and ramp-generators for generating x- and y-deflection. Either a Hewlett-Packard HP 1304A, a HP 1310A, or a Joyce CRT X-Y-Z display unit are used depending on the required screen size and maximum luminance. The Joyce CRT has an exceptionally high luminance of over 700 cd/m², but we have preferred the HP displays with ca. 10 cd/m² for most studies. The software is compatible with all three displays and is easily extended to allow the use of other display types.

THE GENERATION OF STIMULUS PATTERNS

Digital stimulus generation permits a flexibility and ease of realization which is not achieved with analog equipment. Indeed, once the basic technique is mastered, new stimuli can be added by minor software modifications in dedicated program modules. Any one-dimensional spatial wave form with temporally periodic modulation can be generated in the present system. This does not only include sine-wave, square-wave and more complex spatially periodic wave-forms (e.g., the contrast modulated gratings used by Bodis-Wollner & Hendley[4]), but also bars of varying width, Gaussian windows, etc. Temporal envelopes can be sinusoidal, square-wave shaped, Gaussian, and others within certain temporal constraints (see below). Digital signal generation poses restraints on stimulus parameters which are different from those known from analog signal generation. Temporal stimulus sampling rate, frame rate, and temporal stimulus periodicity have to be interdependently selected in order to avoid artifacts.

Sampling Problems

Let us first illustrate the concepts involved in the example of generating phase-alternating sine-wave gratings on an *XYZ* display. Figure 1a, in the upper trace, shows CRT beam intensity as a function of time and in the lower trace shows the *x*-deflection voltage which corresponds to the horizontal position on the screen. As the beam moves across the screen, intensity varies sinusoidally, producing the spatial modulation. At the end of each frame, the beam is dark in order not to be visible during its return. Since the display of a single frame takes a nonzero amount of time, temporal modulation of the image can, like in a movie, only be achieved in a sampled way. In the example, a slow (8 Hz) sinusoidal variation in contrast, as shown in the middle trace, is desired. Each frame is thus displayed with a different contrast (upper trace) the third frame having zero contrast for example. Figure 1b shows this temporal modulation in a different scale.

The frame rate may be considered to be the sampling rate of temporal modulation (which is not strictly correct because the frames are not displayed instantaneously). From the sampling theorem one would, therefore, expect a maximum temporal modulation frequency of half the frame rate. Unfortunately, this is only true when the analog signal is reconstructed from the digital values in a way implied by the sampling theorem. This requires the convolution of the sampled signal with a sine-function, and is computationally much more complicated than the usual way of reconstructing the signal by simply scanning the digital buffer with a D/A converter (for details see Appendix). With the latter conventional method, which we also use, low temporal frequencies due to aliasing are visible. They can be avoided, however, by using only modulation frequencies which are integer fractions of the sample frequency (i.e., frame rate). In the example, the frame rate is 64 Hz. The corresponding Nyquist frequency is 32 Hz, and possible modulation frequencies are 32, 21.3, 16, 12.8, 10.6, 9.1, 8 Hz, etc. While this is a good solution, one is limited in the choice of possible temporal modulation frequencies and there is the side effect that the spacing of possible values increases for the higher values closer to the Nyquist frequency. In our system we have implemented temporal stimulation frequencies which are dividers of 8 Hz (corresponding to 16 reversals per sec).

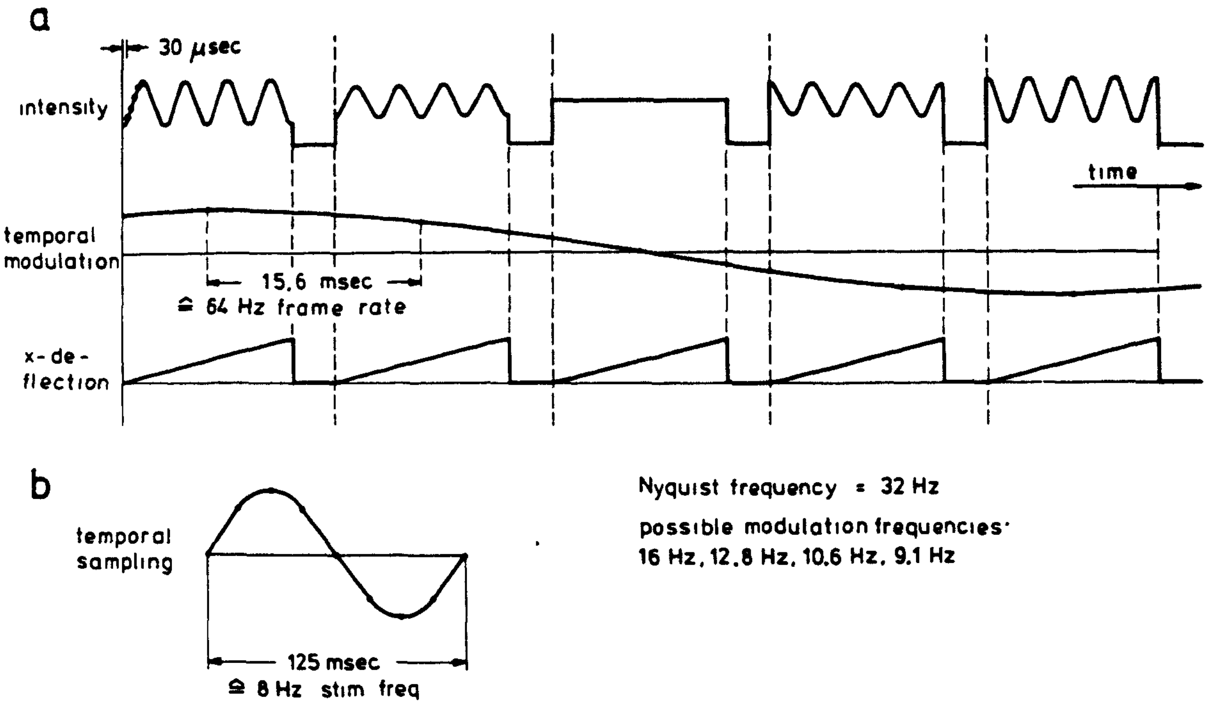


Figure 1. Generation of phase-alternating sine-wave gratings on an *XYZ* display **(a)** Upper trace shows beam intensity (*z* signal), sampled at a high rate (30 μsec), as a function of time Lower trace shows *x* deflection, each ramp sweeping the beam once across the screen thus producing a frame The middle trace shows the desired temporal contrast modulation It is achieved by displaying each frame with a different contrast (i e , sine amplitude in the upper trace), where the contrast value is taken as a sample from the middle trace Temporal modulation is shown again in a different scale in **(b)**.

When arbitrary modulation frequencies are desired, the frame rate cannot be held at a fixed value. Changes should not be achieved by varying the interval between frames, while keeping the sweep time per frame constant. The screen drawing time of the display beam per unit time would then vary and this would lead to a variation in mean luminance. The mean drawing time should be held constant while the *sweep* time is varied. The frame rate has to be chosen well above the flicker fusion frequency. One format for this is to define an interval (say 64 to 80 Hz) within in which the frame rate may vary.

A technical implication of having a variable frame rate is that it is necessary to have the ramp generator which produces the *x*-deflection controlled by the computer. This can be accomplished by letting the computer itself produce the ramp signal.

The maximum frame rate is limited by the amount of time needed for scanning a complete frame. This is determined by the number of spatial samples multiplied by the time to move one sample out to the D/A converter. Using a polling technique, 31 μsec can be achieved for an LSI-11/2 CPU. Given a spatial resolution of 500 points, this results in a frame rate of 64 Hz. Using an interrupt technique instead of polling would greatly simplify the overall programming but the maximum achievable frame rate would then only be 31 Hz. Since the LSI-11/23 operates about twice as fast as the 11/2, an interrupt approach seems possible.

Producing sine-wave signals by software is easy, since all stimuli are prepared offline before the experiment and there is no time constraint. But when a number of stimuli needs to be prepared, a lookup technique can significantly reduce preparation time and make programming easier. This is accomplished by filling a fairly large buffer with one single period of a sine wave at high resolution. Subsequently, all gratings are derived from this lookup table.[20] Different spatial frequencies are obtained by stepping through the lookup table not one by one but with arbitrary step widths (corresponding to phase angles), say every second or third value, or, conversely, taking every value twice or three times. These phase angles need not even be integer multiples or divisors of one. One can take any 2.6th value, for example, and when it does not fall onto a sample, take the nearest value (e.g., 1; $1+2.6=4$; $1+2\times2.6=6$; $1+3\times2.6=9$, etc.). The errors introduced by this method depend on the length of the lookup table. With a buffer length of 512 the error can be neglected for practical purposes (cf. Moore[11]).

Pattern Contrast

Before the z-signal is sent to the CRT, the amplitude is scaled by taking into account the D/A conversion factor and the z-voltage required for a specified contrast. In the simplest way, a full swing z-voltage for extrapolated 100% contrast is specified as a basis for this conversion. Input voltages must not exceed the display's linear range. The luminance corresponding to the mean z-voltage U_{mean} depends for most CRT displays on several knob settings, which are usually set so that zero volts corresponds to the middle of the linear range. Grating waveform voltages are then purely ac. For an ideal linear dependency, contrast can be determined by the formula

$$\text{Contrast} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{(U_{\max} - U_{\min})/2}{U_{\text{mean}} - U_{\text{cutoff}}}$$

where the I's are intensities and U_{cutoff} is the extrapolated voltage value for zero intensity.

To fully compensate for all intensity/voltage nonlinearities of a given display, an amplitude lookup table is needed. Such a technique of calibration is called "gamma correction." Its result, however, would be strictly valid for only one location at the screen. This is why we decided not to use gamma correction. In cases where greater precision is required, it could be added in the stimulus generating programs. The sizeable amount of contrast degradation for high spatial frequencies due to the limited spatial resolution of CRT displays should then also be taken into account.[12]

Sampled Sweep Technique

A continuous sweep technique changes a specified stimulus parameter continuously during recording. The sampled equivalent of this is to have a set of stimuli differing in the value of just one parameter, and to rapidly present one stimulus after the other. A variety of such sets of stimuli can be prepared, with the stimuli in different sets differing in the value of another parameter. We have, for example, studied the dependency of VEP amplitude on spatial frequency at several contrast values.[23] One set contained 18 stimuli differing in spatial frequency, and seven such sets for different contrast values were used.

All the necessary stimuli are prepared at the beginning of a recording session and stored in memory. The maximum number of stimuli is thus limited by the amount of memory storage. The experimenter can choose either to have fine resolution in the independent variable (i.e., many stimuli), and few graphs, or to have more graphs with coarser resolution. In the present configuration, 256K bytes of memory hold 18 stimuli (of 500 points spatial resolution and eight frames temporal resolution; eight frames constitute one 8-Hz-modulation period at 64 Hz sampling rate). Much more memory is of limited value because recording time becomes another bound on the number of stimuli to be presented.

THE ACQUISITION OF VISUAL EVOKED POTENTIALS

The VEP acquisition routine fetches the prepared stimuli from memory or floppy, displays them at a certain frame rate, and acquires one sample of EEG per displayed frame. The EEG sampling rate should be an integer multiple or divider of the frame rate for ease of synchronization. Given a frame rate of 64 Hz, this means possible sampling rates of 32 Hz, 64 Hz, 128 Hz, etc. The main VEP signal components lie at the first and second harmonic for 8-Hz stimulation. The Nyquist frequency should, therefore, be well above 16 Hz. This eliminates a sampling rate (equal to twice the Nyquist rate) of 32 Hz as a possible solution. High sampling rates, on the other hand, are not feasible when raw data is to be stored on floppies. Higher sampling rates are often asked for by EEG practitioners accustomed to transient VEPs since averaged signals with many wiggles look more "realistic." VEP signal energy is small above the second harmonic, however, (at least for our kind of stimulation), and a higher sampling rate than 64 Hz does not yield more information about the signal. (Whereas for any given stimulation frequency the energy drops rapidly above the 2nd harmonic, it is nevertheless possible to elicit VEPs at much higher stimulation frequencies; cf. Tyler et al.[26]) Choosing an EEG sampling rate equal to the stimulation frame rate also greatly simplifies programming. For steady state VEPs with moderate stimulation frequencies, much lower sampling rates are appropriate than those used with transient VEPs.

For the present system, with one channel and 64 Hz sampling rate, the results of 4 to 6 recording sessions fit onto one double-sided double-density 8" floppy disk. The floppy disk storage medium allows very convenient sorting and archiving of the data. Storage of preprocessed data would clearly be more economic but would come at the expense of future possibilities of data analysis. In cases where no further raw data analysis is planned, raw data files can be deleted after averaging.

The Analog Signal Path

The preamplified EEG is fed into a 12 bit A/D converter and is bandpass-filtered between 3 and 25 Hz. Contrary to what is often assumed, the noise level of the preamplifier is not of critical importance. Since VEP analysis methods are designed to detect low energy signals in background EEG noise, amplifier noise would be a problem only if it amounted to an appreciable fraction of the EEG voltage and this is usually not the case. The analog prefiltering is necessary to avoid aliasing, that is, the attenuated EEG power above the Nyquist frequency has to be lower than a tolerable artifact level. For example, with a Nyquist frequency of 32 Hz, EEG power at 48 Hz will "mirror" around 32 Hz to produce an alias at 16 Hz. To achieve an aliasing error of less than 10% at 16 Hz, a 20 dB attenuation at 48 Hz is required. With the filter cutoff frequency set to 24 Hz, 48 Hz is one octave above this value, resulting in a required filter steepness of 20 dB/octave. Obviously, the lower the desired sampling rate, the steeper the analog filter's roll-off slope has to be. A steep roll-off characteristic is, however, accompanied by frequency-dependent temporal phase shifts near the cutoff frequency. The latter may amount to several full 360 degree revolutions. These measurable phase shifts have to be taken into account when temporal phase values are analyzed.

The EEG is continuously monitored on an oscilloscope to detect any faults in the setup (usually loose electrodes, broken electrode wires, and marginally loaded batteries in the preamplifiers). In our experiments, the only means of artifact rejection was a check on EEG-clipping at the A/D-converter. More elaborate schemes are desirable for work with children and infants. They can be implemented as additional analysis stage prior to averaging. For work with infants, recording can be temporarily suspended by pressing a button when the child is not watching the screen.

Sweep Strategies

The sweep facility leaves several choices to the experimenter. The spacing of the sweep variable, and the choice between linear, logarithmic, or any other progression, are determined during stimulus preparation. With a given set of stimuli, several strategies for presentation can be pursued. The program can provide either a rapid sweep rate (i.e., one with few stimuli or short trials) with averaging across many sweeps, or a slow sweep rate. The sweep can either be unidirectional, or it can alternate between upwards and downwards. It can employ every stimulus of a prepared set, or only use every n^{th} stimulus. The use of a random selection of stimuli is also possible. Since the signal-to-noise ratio increases with the square root of the net total recording time (i.e., the number of trials times trial duration), a given S/N-ratio is achieved either with many short or few longer trials. To keep variations during the sweep low, fairly short trials should be used. On the other hand, the use of a short trial time leads to an increase in overall recording time: A change of the stimulus takes approximately 1 sec; then, at the beginning of each trial the first second of the EEG is discarded to allow for the evoked response to reach a steady state. Thus, every trial is accompanied by a time overhead of 2 sec. We use mostly 2-sec trials and regard the corresponding overhead of 100% as tolerable.

With the older continuous sweep technique, the evoked response can never reach a true steady state, which leads to a "smearing out" of the response over the swept variable. We do not currently have data on how much time should be discarded at the beginning of a trial but infer from the duration of transient VEPs that 500 msec should be sufficient.

THE ANALYSIS OF THE EVOKED RESPONSE

The program system performs the VEP analysis in three steps: Averaging over individual trials (e.g., 2 sec stimulation), Fourier analysis of averaged trial data, and the subsequent calculation of mean spectral components and standard errors. The latter are determined across trials with identical stimulation parameters. Results are plotted as a function of the independent variable chosen during stimulus preparation. An example of this is shown in Figure 2a where the swept variable is spatial frequency. Figure 2b shows the corresponding phase plot. Here it is important to note that temporal phase angles are only defined modulo 2π. This lack of uniqueness of phase values is removed by assigning the values in a way that the distance in phase between adjacent data points is minimized (for details see Strasburger[21 22]).

Only a few frequency components result from the Fourier analysis, due to the comb filter effect of averaging (cf. Strasburger [21 22]); that is, only integer multiples of the averaging frequency remain. For our averaging period of 125 msec, these are the 8 Hz, 16 Hz and 24 Hz components. Higher frequencies do not occur due to the sampling rate of 64 Hz.

It is also important to note that the program may perform the averaging over spectral components either by calculating scalar means or vector means of individual components. A scalar mean is computed as an average over amplitude values, whereas a vector mean is obtained from averaging over the sine/cosine representations of spectral components with the subsequent conversion to an amplitude/phase representation. The main advantage of vector averaging is that it preserves the linearity of the Fourier transform, while this is not the case with scalar averaging. From this it follows that vector averaging and

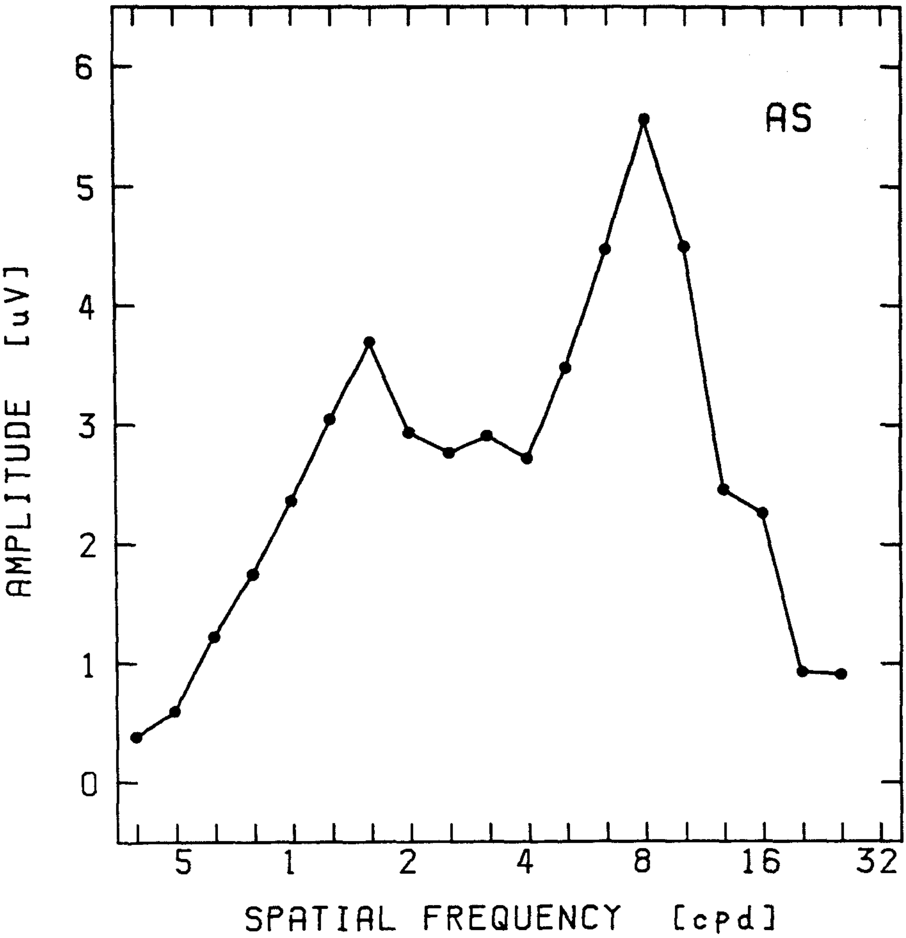
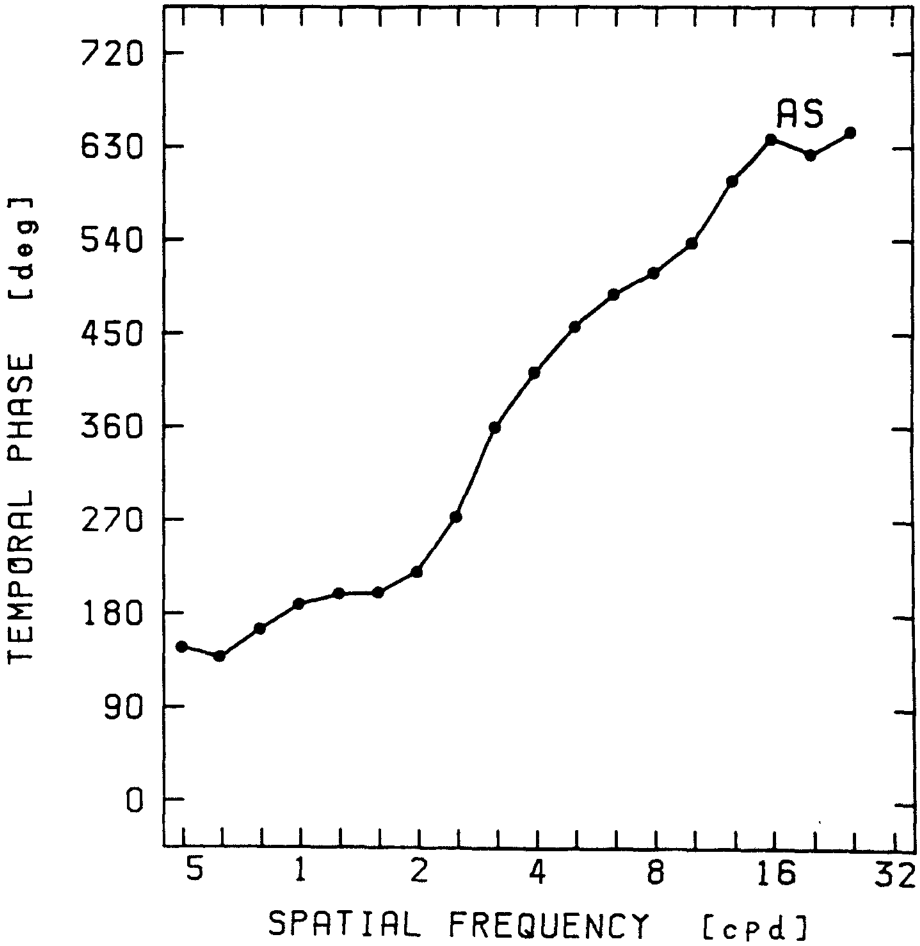


Figure 2. Amplitude **(a)** and temporal phase **(b)** of the 16-Hz component plotted relative to stimulus spatial frequency. Stimulation with phase–alternating sine wave gratings, 8 Hz (16 rps), 40% contrast, 6 sweeps with 2 sec stimulation for each spatial frequency value.



The stimuli are described by

1. the name and version of the generating program;
2. their type (sine-wave, square-wave, etc.);
3. temporal frequency, spatial frequency, contrast, viewing distance and angle, display unit;
4. the set to which the stimulus belongs and the difference between sets;
5. the sweep variable and its value for the other stimuli of the set; and
6. comments concerning the stimuli.

The recording session protocol contains the name of the subject and the experimenter, the recording date, the eye tested, the pre-amplification factor, and remarks concerning the session.

The present system uses a scheme employing unencoded text and descriptive parameters preceding each data file. Each program part separates these data from its input, passes them along to its output file, and adds to them all information describing its own working. As a result, each data file carries all information which is necessary for its interpretation. The FFT programs, as current final analysis steps, offer options to print out the results together with this documentation. These output sheets are kept for filing together with the corresponding graphs. The result data files are passed along to an interactive general purpose graphics system (Graftalk, Redding Group Inc.) running on a CP/M computer. Reformatting programs (ReforMatter under CP/M, MicroTech Exports, or CPMRT under RT-11, DECUS) are used for this file transfer via 8″ diskettes. The results can be inspected on a graphics terminal and then plotted.

A user's manual including a technical description is available in the English and German languages. Additionally, the program sources contained detailed information. Source documentation is in English. The user's interface is in German; an English version is in preparation.

Portability

The program system is designed to run on the PDP-11/LSI-11 family of minicomputers. Since the main part of the system is written in Fortran-IV, porting to 16-bit microcomputers should be straightforward. Apart from some peculiarities of DEC Fortran, problems reduce to the compatibility of process peripherals (A/D, D/A, Digital I/O, and programmable clock). Dependencies on these are concentrated in the real time portion of the main data acquisition routine and are well-documented there. The current system is configured for LSI-11/2 and LSI-11/23 systems with Data Translation peripherals.

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EQUIPMENT SOURCES

1. Data Translation, Inc., 100 Locke Dr., Marlboro, MA 01752
2. Digital Equipment Computer Users Society (DECUS), 249 Northboro Road, BP02, Marlboro, MA 01752
3. Hewlett-Packard, 3200 Hillview Ave., Palo Alto, CA 94304.
4. Innisfree, Ltd. John Daugman, Harvard University, Mass.
5. Joyce Electronics Ltd., 52 Greystoke Road, Cambridge, CB1 4DS, England.
6. Keck & Fritsch Ass., 2332 So. Belvoir Blvd., Cleveland, Ohio 44118.
7. MicroTech Exports, 467 Hamilton Ave., Suite 2, Palo Alto, CA 94301.
8. Princeton Applied Research, POB 2565, Princeton, NJ 08540.
9. Redding Group, Inc., 609 Main Street, Ridgefield, CT.
10. Rockland Systems Corp., 230 West Nyack Road, West Nyack, NY 10994.
11. Tektronix, Inc., POB 1700, Beaverton, OR 97075.

APPENDIX

Aliasing with Synthesized Waveforms in Spite of Sufficient Sampling Rate

When an analog signal is digitized, it follows from the sampling theorem that aliasing will be absent with the sampling rate chosen sufficiently high, namely more than twice the signal's maximum frequency component. This is called the Nyquist criterion. However, for the inverse operation—reconstructing an analog signal from its sampled values—the Nyquist criterion, although a necessary condition, is not a sufficient one for the aliasing to be absent:

The sampled signal has an infinite frequency spectrum. Before or after conversion to an analog signal, the aliasing components are to be filtered out by a low-pass filter with a cutoff frequency slightly below the Nyquist frequency. In the temporal or spatial domain, this corresponds to convolving the signal with a sine function (sin $(x)/x$). In contrast to this, the actual reconversion by scanning the buffer with a sample-and-hold D/A converter is equivalent to a convolution with a *square-wave* which has the width of the sampling period. In the frequency domain, this corresponds to multiplying the spectrum with a sine function instead of the desired low-pass function; the sine function only partly filters out the aliasing components.

Since the sine function has zeroes at integer multiples of the modulation frequency, aliasing can be avoided by choosing an integer ratio of sampling and modulation period. The two other methods to avoid aliasing are not appropriate in the present context:

1. Reconversion by convolving with a sine function. This is computationally involved and therefore not recommended.
2. Low-pass filtering of the *analog* signal. In our case, for the synthesis of temporal modulation of (spatial) images, this is not possible since then the spatial modulation, corresponding to a high temporal frequency, would also be filtered out.