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Human Electroretinogram Responses to Video Displays, Fluorescent Lighting, and Other High Frequency Sources

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ABSTRACT

Time-averaged human electroretinogram (ERG) responses were determined for several workplace visual stimuli which are temporally modulated at rates exceeding the perceptual critical fusion frequency (CFF). A clearly identifiable synchronous response was in evidence for a video display terminal (VDT) stimulus operating with a refresh rate as high as 76 Hz. A directly viewed fluorescent luminaire with controllable driving frequency elicited a synchronous response at rates as high as 145 Hz. In addition, an intense stimulus created by modulating the light from a slide projector produced responses at least as high as 162 Hz. The implications of these high-frequency responses as representing a potential basis for visual symptoms are discussed.

Key Words: electroretinogram, video displays, fluorescent lamps, flicker, autoregression, photovoltaic effect

The frequency at which a temporally periodic time-varying light stimulus ceases to be perceived as flickering is referred to as the perceptual CFF. The CFF can vary, depending on various physical characteristics of the stimulus, such as intensity, modulation, waveform, chromatic distribution, size and position of the light source, and on the age, health, and psychological status of the observer.[1–5]

Evidence exists, for both humans and other vertebrates, that components of the visual pathway continue to respond synchronously to periodic light stimuli oscillating at frequencies above the perceptual CFF. For example, in studies of rabbit visual evoked cortical potentials[6] and of cat retinal and lateral geniculate nucleus (LGN) neurons,[7–9] phase-locked responses to periodic light stimuli at frequencies above 100 Hz have been reported. Studies of human subjects have claimed evoked potential responses and ERG responses somewhat above perceptual fusion.[5,10–15] Psychophysical responses to sources oscillating above CFF have been elicited by observing low-frequency beats created by stimulating the retina simultaneously with periodic oscillating light as high as 125 Hz and electrical current sources.[16] In addition, Brindley[16] observed beats produced by harmonics of the intermittent light when the alternating current was oscillating as high as 450 Hz. (In Brindley's study the ability to produce such a beat response requires simultaneous sensitivity to both the electrical and light oscillations.) Thus, there is considerable evidence for responses to periodic light stimuli at frequencies above perceptual fusion within elements of both human and animal vision systems.

The ubiquitous VDT, whose central visual component is the cathode ray tube (CRT), provides its viewer with a periodic visual stimulus that is generally not perceived as flickering. The standard practices are to refresh the screen at a rate of 60 Hz in the U.S. and 50 Hz in many other countries. This means that for the VDT in the U.S., once every 1/60 s (16.67 ms) the electron beam starts to sweep across the screen from the top left corner and runs through the screen to the bottom right corner. Thus, any individual letter presents a periodic visual stimulus flickering at 60 Hz (disre-

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garding the small spatial displacement resulting from the interlacing). Because typical phosphor decay times are short compared with 16.7 ms, the viewed stimulus has a very high modulation (mathematically this would be 200% modulation if it was defined as the ratio of the amplitude of the first harmonic to the average value).[3] For the CRT the refresh rate is such that there is generally no perception of flicker when it is viewed directly; however, the actual rate of oscillation is well within the range of frequency values that have been mentioned above as producing synchronous responses in some neural components of the visual pathway.

Recent studies in the U.K.[17] have reported on the lighting for office workers concerned with the incidence of headaches and eyestrain. A double masked design was used comparing standard fluorescent lighting of 50 Hz that produces 100 Hz flicker with high-frequency (32 kHz) lighting. Under the high-frequency lighting the average incidence of reported headaches and eyestrain was reduced more than 50% and this could be indicative of an effect of flicker on vision function.

Given the evidence that under experimental conditions the human, rabbit, and cat visual systems show some response to light modulation at frequencies typical of light oscillations occurring in the workplace, we set out to determine directly whether measurable ERG responses could be elicited from viewing common workplace equipment such as video displays, fluorescent lighting, and a more intense experimental source.

The first specific objective of our studies was to examine the averaged ERG responses of subjects viewing text on a VDT with its luminance and contrast typical of workplace conditions but in the absence of any ambient lighting. For this study we measured ERG responses over a range of refresh rates from 46 to 81 Hz. The second specific objective of our studies was to examine whether the common source of interior lighting, the fluorescent lamp, could give rise to a synchronous ERG response. Although the frequency of light modulation (typically 100 Hz in Europe and 120 Hz in the U.S.) of these lamps is double that of the VDT refresh rate, the intensity and the field size of the illuminated scene is much greater and thus measurable responses to this stimulus may be possible. The third specific objective was to examine whether ERG responses could be obtained at even higher frequencies than those found by microelectrode recordings in animals. To accomplish this a more intense stimulus was introduced (slide projector beam system interrupted by a rotating sector disc).

With the VDT stimulus, subjects showed clearly identifiable synchronous ERG responses at refresh rates as high as 76 Hz. For the fluorescent lamp stimulus, synchronous responses up to 145 Hz and possibly even higher frequencies were demonstrated. With the more intense source, responses were found at least as high as 162 Hz.

METHODS

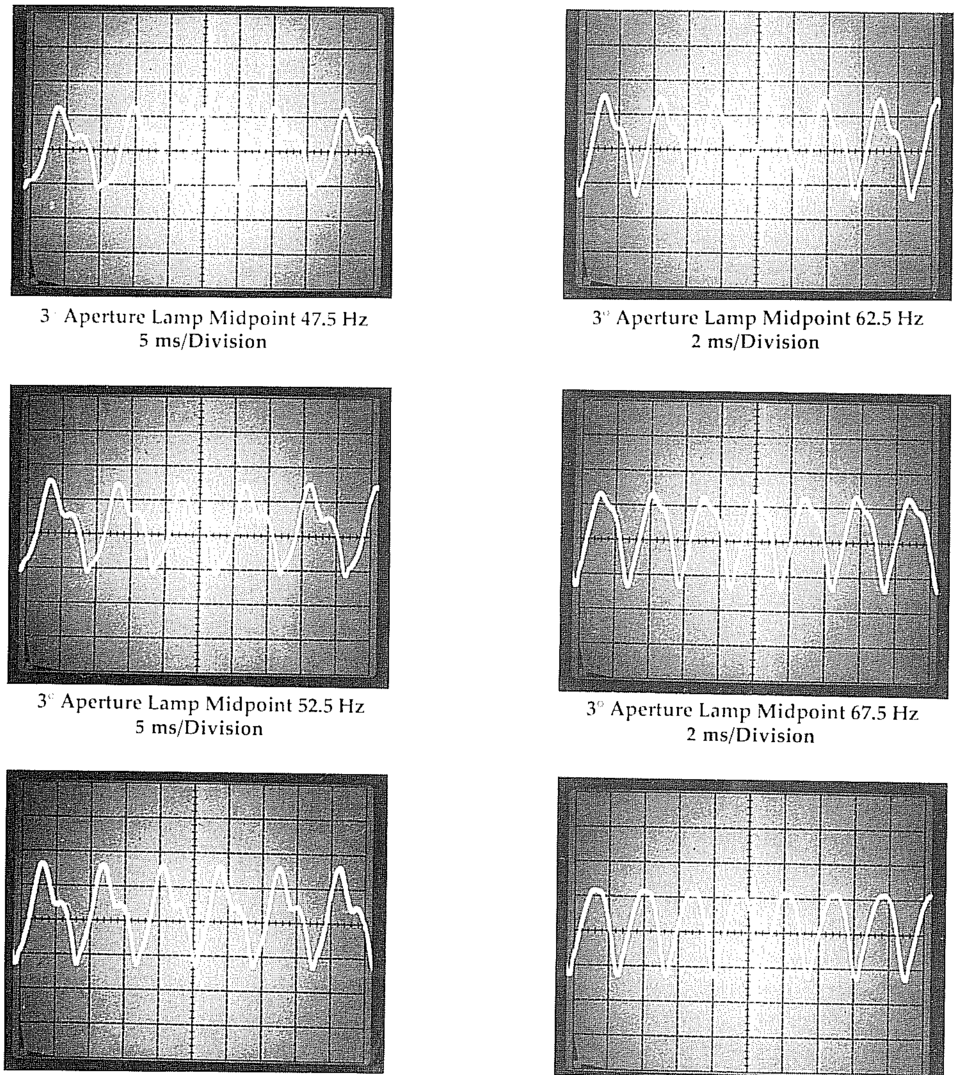
VDT Stimulus

The visual stimulus was displayed on a MicroTerm Inc. MIME-I white-phosphor video terminal which was modified so that its refresh rate could be varied between 46 and 81 Hz. A grounded metal screen (1.3 cm mesh galvanized iron) was placed in front of the CRT to minimize electromagnetic field (EMF) contamination of the ERG signal. To enable signal averaging when measuring ERG's, a train of pulses, phase-locked to the VDT refresh rate, was used to trigger data acquisition cycles in the Nicolet ERG instrumentation. (Nicolet Compact Auditory Electrodiagnostic System with version 1.4 software.) The ERG measurement protocols and system are discussed below.

The arrangement of the text character display was chosen to achieve the maximum power at the fundamental temporal frequency for the space-averaged luminance distribution. An adequate signal was found where the first 12 lines of the top half of the display screen were filled with uppercase "O" characters while the lower half of the screen was blank. Thus with a period of $1/60$ s to sweep the screen, the upper 12 lines of the screen are lit on average for $1/120$ s and this is followed by darkness for the remaining $1/120$ s with the cycle repeating 60 times per second. Thus, the light signal provoked by the VDT approximates a 60 Hz square wave with a 50% duty cycle. A smaller area of the upper case letters of size 1° presented a waveform which appears as a series of sharp spikes occurring every $1/60$ s and decaying exponentially to less than 10% in less than 1 ms. The space- and time-averaged luminance of the 12-line test display area was measured with a Pritchard spectrophotometer (model 1980BX-SS) and was 16.2 cd/m^2, whereas the time-averaged luminance of an individual pixel was measured as 90 cd/m^2. The display was viewed in a darkened room to eliminate contamination of the data from the effects of ambient light source flicker and to maximize the effective modulation of the visual stimulus. The intensity of retinal stimulation and the magnitude of the residual radiated EMF originating from the shielded VDT are both distance-dependent and we determined in preliminary experiments that a 1-m viewing distance provided satisfactory signal-to-noise ratio (see below for discussion of potential EMF contamination). The 12-line display subtended a visual angle of 5° by 12° at 1 m.

Fluorescent Lighting Stimulus

In this case the VDT was replaced by a much larger size stimulus, namely a fluorescent lamp fixture that held two standard F40 T12 daylight spectrum lamps. These lamps have 100% light modulation with the primary rate of oscillation being twice the line voltage frequency. The two lamps were driven in phase in order to maximize the possibility of an ERG response. The fixture, includ-



3° Aperture Lamp Midpoint 47.5 Hz
5 ms/Division

3° Aperture Lamp Midpoint 62.5 Hz
2 ms/Division

3° Aperture Lamp Midpoint 52.5 Hz
5 ms/Division

3° Aperture Lamp Midpoint 67.5 Hz
2 ms/Division

3° Aperture Lamp Midpoint 57.5 Hz
5 ms/Division

3° Aperture Lamp Midpoint 72.5 Hz
2 ms/Division

Figure 1. Time-dependent waveforms of the fluorescent lighting at the test frequencies 47.5, 52.5, 57.5, 62.5, 67.5, and 72.5 Hz. The photometer was directed at the lamp midpoint with a 3° aperture. The fundamental component in the light waveform can be seen for the 47.5 Hz by the alternating height of the secondary peaks that appear to the right of the primary peaks. The grid for the 47.5, 52.5, and 57.5 Hz traces have 5-ms intervals, whereas the grid for the 62.5, 67.5, and 72.5 Hz traces have 2-ms intervals. Measurements have been taken with a Pritchard Spectrophotometer model 1980 BX-SS.

ing the lamps, was enclosed in a grounded wire mesh in order to minimize the radiated EMF. The Nicolet system was triggered by direct electronic means from the variable frequency power supply that drove a standard F40 ballast, thus assuring that averaging of the collective ERG responses was carried out with a fixed phase with respect to the cycle of light variation.

The operating frequency of the lamps was varied at 5-Hz intervals between 47.5 and 72.5 Hz with a California Instruments *Invertron* ac power source, model 501TC, with a precision oscillator model 850T which produced lamp light oscillations at primarily double the operating frequency (95 and 145 Hz). Data were taken from all runs at intervals of 5 Hz in the lamp operating frequency.

The lamp fixture was viewed directly from a distance of 1 m and it subtended an angle of 7° by 53°. The ballast input voltage was set at its highest value for the 3 lower frequencies and this yielded measured luminances (in units of 10^3 cd/m^2) of 1.98, 2.23, and 2.49, respectively, for 47.5, 52.5, and 57.5 Hz, whereas at the three highest frequencies the luminance had the same value of 2.6×10^3 cd/m^2. The luminance measurements were made with the Pritchard spectrophotometer with the aperture set to cover nearly all the lamp tube surface.

The waveform of the light emitted from the fluorescent fixture was monitored with the same Pritchard spectrophotometer and the signal was transmitted to a Tektronix oscilloscope (model no. 5113) via the video channel for waveform analysis. Fig. 1 shows the waveforms for the 6 test frequencies used in the study, 47.5, 52.5, 57.5, 62.5, 67.5, and 72.5 Hz. At the lower frequencies the variable frequency power supply used to power the lamp ballast causes a large second harmonic in the current which in turn causes an asymmetry in the voltage and, hence, in the light waveform. The waveforms of the emitted light from the fluorescent lamp fixture (Fig. 1) show a distinct component at the fundamental or ballast frequency, especially at the lower ballast frequencies indicating the voltage asymmetry in the lamp system operation. A spectral power analysis was performed on the waveforms to determine the amount of power in the fundamental and other harmonics relative to the second harmonic. These values are shown in Table 1 for the six test frequencies with the amplitude of the second harmonic (the normal frequency of light modulation) normalized to unity for each test frequency.

Sector Disc Stimulus

This stimulus was used to examine the possibility that ERG responses can be measured at frequencies that are substantially higher than the perceptual CFF. In this study the stimulus was a beam of light from a slide projector which provided a more powerful stimulus than the fluorescent lamps. The light was temporally modulated at frequencies ranging from 80 to 200 Hz by means of a rotating sector disc placed before the lens that provided 100% modulation and a waveform that was approximately sinusoidal. The subject was situated 1 m from the projector and looked directly into the lens along its axis. The lens provided approximately a 2° field of view; the lamp was operated from a dc source in order to eliminate temporal variations in light output from the projector and hence avoid any beating effects in the stimulus. This system provided much higher luminance than the VDT or fluorescent lamps. Measurement with a Spectra Pritchard photometer (20 min arc aperture, 1 m from source) gave average values of 2.2×10^6 and 4.4×10^6 cd/m^2 at the two levels used. These levels are referred to as reduced and high brightness conditions below. Using the blue light hazard spectral function[18] provided by the American Conference of Governmental Industrial Hygienists (ACGIH), the spectral power distribution of the projector lamp, and the solid angle subtended by the projector surface at the subject eye, we calculated that exposure times should be less than about 10 min for the high brightness condition. Total exposure time was limited to a net value of 65 s at the high brightness condition and 118 s at the reduced brightness condition.

ERG Measurement

ERG's were measured, stored, and displayed on the Nicolet system. A Burian-Allen bipolar contact lens electrode was worn by the subject, and the cable assembly between the electrode and Nicolet unit was shielded to minimize pickup of stray EMF's originating from the VDT or fluorescent lamps. For most data collection, the Nicolet amplifier was set at maximum sensitivity. Internal bandpass filtering was used (30 to 100 Hz bandpass in VDT experiment, and 30 to 250 Hz in fluorescent light and rotating-disc experiments) together with automatic artifact rejection and an internal mains (60 Hz) frequency notch filter (except during the 61 Hz VDT exposure).

In the VDT experiments, ERG's were measured at refresh rates between 46 and 71 Hz (5-Hz intervals) for one subject (RWR, a 50-year-old normally sighted male) and between 61 and 81 Hz for a second subject (AMB, a 20-year-old female with normal vision). The duration of each data acquisition period was rounded up to always include at least two refresh periods (the Nicolet data acquisition system collects 512 sequential data points. The duration of the data acquisition window can only be varied in 1-ms steps per 500 data input channels. In the experiment the duration of the 500 channel period was set equal to 2 refresh periods as rounded up to the nearest millisecond, varying from 44 ms (46 Hz refresh rate) down to 25 ms (81 Hz refresh rate). In each run, except as noted below, the number of data acquisition periods that was averaged was equal to 200 times the refresh rate, varying from 9,200 periods (46 Hz refresh rate) to 16,200 periods (81 Hz refresh rate). This corresponds to an accumulated sample time of 400 s of artifact-free data. In order to minimize the period of contact lens wear, runs at the lower refresh rates were sometimes shortened if there was an obviously robust ERG response. At each refresh rate, two runs were performed, one being the test condition with the VDT viewed directly, and the second was a control condition with the VDT covered with opaque cloth and this condition allowed us to assess the level of EMF contamination.

TABLE 1. Relative amplitudes of the Fourier components of light output of the fluorescent lamps operated over a range of driving frequencies from 47.5 to 72.5 Hz.[a]

Order	Frequencies					
	47.5	52.5	57.5	62.5	67.5	72.5
1	0.2066	0.1673	0.0591	0.0725	0.0721	0.0169
2	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
3	0.2586	0.1341	0.0504	0.0449	0.0567	0.0120
4	0.3350	0.3733	0.4020	0.3320	0.2877	0.2307
5	0.0820	0.0648	0.0215	0.0026	0.0443	0.0177
6	0.2109	0.1754	0.1468	0.1363	0.1004	0.0811
7	0.1046	0.0339	0.0128	0.0295	0.0149	0.0075
8	0.0465	0.0508	0.0445	0.0387	0.0437	0.0567
9	0.0826	0.0121	0.0152	0.0373	0.0113	0.0126
10	0.0588	0.0492	0.0600	0.1921	0.0323	0.0228

[a] Values are relative to the amplitude of the second harmonic (usual frequency of light flicker) of the driving frequency.

The fluorescent lamp and the high intensity sector disc experiments were carried out with subject AMB only. The control conditions were established by covering the fluorescent lamps with an opaque black cloth or by placing opaque cardboard in front of the projector source and otherwise maintaining subject and stimulus as in the test condition. The ERG responses for the fluorescent lamps were averages of 2000 data acquisition cycles, whereas for the sector disc the responses were averages of 500 cycles at the lowest modulation frequencies and up to 4000 cycles for the highest frequencies.

In our analysis we have assumed that there is no significant delay between a trigger pulse and the beginning of a data acquisition cycle in the Nicolet instrumentation. We confirmed this by a simple test. When we provided simultaneous pulses as trigger and electrode inputs, we were unable to detect any measurable delay, and we estimate any residual latency would have an upper limit of approximately 1/10 of a millisecond.

RESULTS

VDT Stimulus

Graphic traces of the resultant average ERG voltages as determined by the Nicolet system for subjects RWR and AMB are shown in Fig. 2. In each of the 10 plots the upper trace(s) shows the responses to the directly viewed VDT stimulus, whereas the lower trace(s) shows the control condition with the occluded screen. The time scale of the abscissa has been adjusted for each value of the refresh rate, so that two complete cycles (one data acquisition period) are shown on each plot. Inspection of the results for RWR clearly reveals the presence of a synchronous reponse for refresh rates up to 66 Hz but no obvious signal at 71 Hz. For subject AMB, a synchronous response is evident in Fig. 2 at frequencies as high as 76 Hz. The number of sweeps used for obtaining this average ERG response was the same as for subject RWR at 71 Hz. However, for the 61 and 66 Hz conditions, it was reduced by a factor of ¼ and ½, respectively, in order to shorten the time needed to wear the ERG lens when a robust response became apparent. Consequently, for subject AMB, there is greater noise seen in the control conditions at these frequencies. More quantitative analyses and statistical treatments are presented below (see Tables 2 and 3).

The presence of a small residual response at the various refresh rates in the control conditions is apparent in many of the graphs. As mentioned above in the Methods description, this residual control response could be amplified or attenuated by the subject moving closer to or further from the VDT. Thus, it is likely that these responses in the control condition are due mainly to residual radiated EMF's which the shielding failed to exclude. Because the VDT was surrounded by a grounded wire cage, we conjecture that the EMF is most probably due to radiated magnetic fields associated with the scribing electron beam. A more quantitative treatment dealing with these residual "signals" is dealt with below in the statistical analyses.

Fluorescent Lamp Stimulus

At the lower operating frequencies the average ERG response voltages displayed in Fig. 3 show that, even with the relatively smaller power of the fundamental (ballast driving frequency) in the stimulus signal (see Table 1), compared to the second harmonic (usual lamp flicker frequency) the ERG response is predominantly at the fundamental frequency. This feature is confirmed by the more quantitative fitting and statistical analyses discussed below. These analyses show that the ERG response amplitudes in the fundamental and second harmonic become of comparable magnitude for the 57.5 and 62.5 Hz frequencies. Because there is much less power in the signal at the fundamental driving frequency (Table 1), this result indicates the greater effectiveness of our stimulus in producing an ERG response at the fundamental frequencies in the vicinity of psychophysical fusion frequency as compared with the stronger stimulus second harmonic frequencies not usually perceived as light flicker. Inspection of Fig. 3 and comparing the 57.5 Hz case with the lower frequencies shows an increasing relative amount of ERG response amplitude at twice the driving frequency (the usually predominant frequency of fluorescent lamp light oscillation). Further quantitative analysis discussed below indicates that this trend continues at the higher frequencies where there is a highly significant amplitude of response at the second harmonic.

Control runs, in which the lamps were covered with a black cloth that prevented any light escape, can produce a signal in the ERG electrode and we attribute this to electromagnetic radiation. The statistical analyses described below show that there is an EMF response but that it is generally much smaller than the ERG response in the presence of direct light, especially at the frequency of the second harmonic (see Tables 4 and 5 below).

Sector Disc Stimulus

For this high intensity stimulus the ERG responses were obtained for 6 test frequencies: 80, 100, 120, 142, 162, and 200 Hz. Fig. 4 shows the ERG response at each frequency for subject AMB. On each graph, the time axis is scaled to represent data collected for two cycles of the stimulus waveform. The presence of a synchronous response is visible at all test frequencies except for the reduced brightness case at 162 Hz (see Table 6).

Statistical Analysis of Results

The primary assumption in the data analysis presented below is that, in the absence of both a visual stimulus and EMF from the VDT, rotating disc, or fluorescent lamps, there is no intrinsic

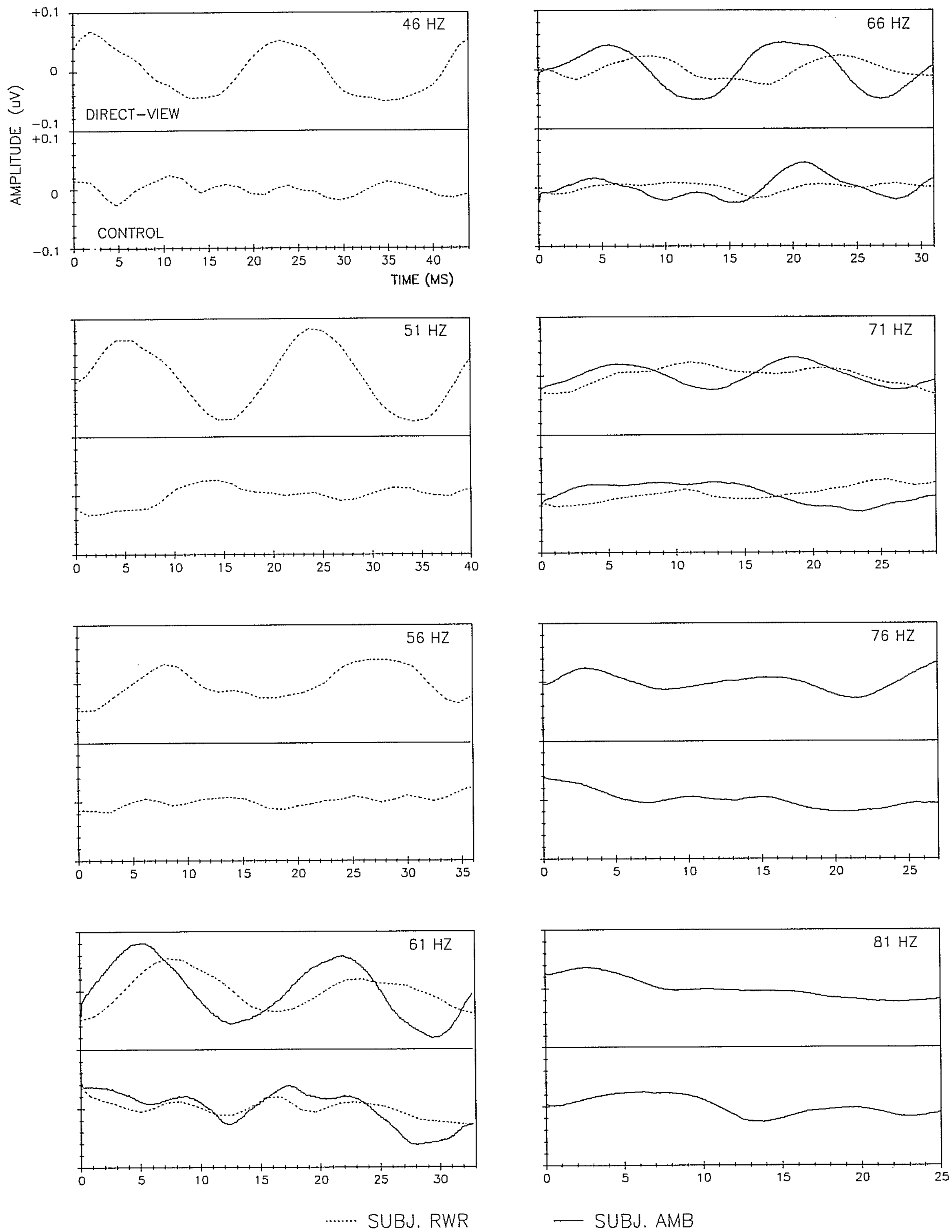


Figure 2. ERG responses to CRT visual stimulus. Amplitudes of the ERG response in microvolts are shown for CRT refresh rates ranging between 46 and 81 Hz. The dc components have been subtracted from all traces, and the direct-view data placed above the control data for clarity. The time axis scale varies inversely with refresh rate with the result that each trace represents data from two refresh periods. The scale of the y axis is identical for all plots. The control condition has ERG lens in the eye, but the VDT is covered with opaque black cloth.

TABLE 2. Responses at the stimulus frequencies from the time series analysis of equation 1 for subject RWR with VDT stimulus.[a]

Run	No. Trials Averaged	Amplitude (nV) Mean value	Amplitude (nV) Standard error	Phase Angle (°) Mean value	Phase Angle (°) Standard error
46 Hz-T	9,200	49.34	3.52	41	4.1
46 Hz-C	9,200	6.16	2.30	220	21
51 Hz-T	10,200	73.47	2.49	−9.3	1.9
51 Hz-C	10,200	6.50	4.89	180	44
56 Hz-T	11,200	28.33	6.16	262	12
56 Hz-C	11,200	4.64	4.40	169	50
61 Hz-T	12,200	34.15	6.74	262	11
61 Hz-C	12,200	2.90	4.79	−82	85
66 Hz-T	13,200	20.27	2.10	238	5.9
66 Hz-C	13,200	6.03	2.44	207	23
71 Hz-T	14,200	10.76	4.28	215	23
71 Hz-C	14,200	7.26	2.58	212	20

The Difference Between Amplitudes for Test and Control Condition

Frequency	Amplitude Difference	Standard Error	Z Score	p Value
46 Hz	43.18	4.22	10	7E-25
51 Hz	66.97	5.48	12	1E-34
56 Hz	23.70	7.56	3.1	0.0008
61 Hz	31.22	8.28	3.8	8E-5
66 Hz	14.23	3.22	4.4	5E-6
71 Hz	3.50	4.99	0.7	0.242

[a] "T" refers to the test condition (subject viewing VDT) and "C" to the control condition (ERG lens in eye but VDT covered with black cloth). Units of amplitude are in nanovolts (10^{-3} μV).

TABLE 3. Responses at the stimulus frequencies from the time series analysis of equation 1 for subject AMB with VDT stimulus.[a]

Run	No. Trials Averaged	Amplitude (nV) Mean value	Amplitude (nV) Standard error	Phase Angle (°) Mean value	Phase Angle (°) Standard error
61 Hz-T	3,052	64.29	2.74	−30	2.5
61 Hz-C	3,155	24.57	12.02	155	29
66 Hz-T	7,112	45.92	2.03	−32	2.5
66 Hz-C	7,120	20.96	6.84	−39	19
71 Hz-T	14,238	22.76	1.34	−57	3.3
71 Hz-C	14,244	5.52	3.66	44	38
76 Hz-T	15,200	21.01	2.83	20	8.7
76 Hz-C	15,200	8.50	2.05	64	13
81 Hz-T	16,200	7.52	1.66	1.1	14
81 Hz-C	16,200	11.82	2.69	253	13

The Difference Between Amplitudes for Test and Control Condition

Frequency	Amplitude Difference	Standard Error	Z Score	p Value
61 Hz	39.72	12.31	3.2	0.0006
66 Hz	24.96	7.13	3.5	0.0002
71 Hz	17.24	3.91	4.4	5E-6
76 Hz	12.51	3.52	3.6	0.0002
81 Hz	−4.30	3.16	1.4	0.09

[a] "T" refers to the test condition (subject viewing VDT) and "C" to the control condition (ERG lens in eye but VDT covered with black cloth). Units of amplitude are in nanovolts (10^{-3} μV).

retinal electrical variation in the output of the ERG electrodes at the test frequencies used. Therefore, any statistically significant response at the test frequency should be due to visual stimulation or EMF from the source.

For each of the three kinds of stimuli, two hypotheses were tested. The first was that there was a synchronous response to EMF, both in the control condition with the stimulus occluded, and in the test condition. The second hypothesis was that the response was greater in the experimental condition than in the control condition due to generation of an ERG signal from the visual stimulation.

The input signal over time, t, in each of the three

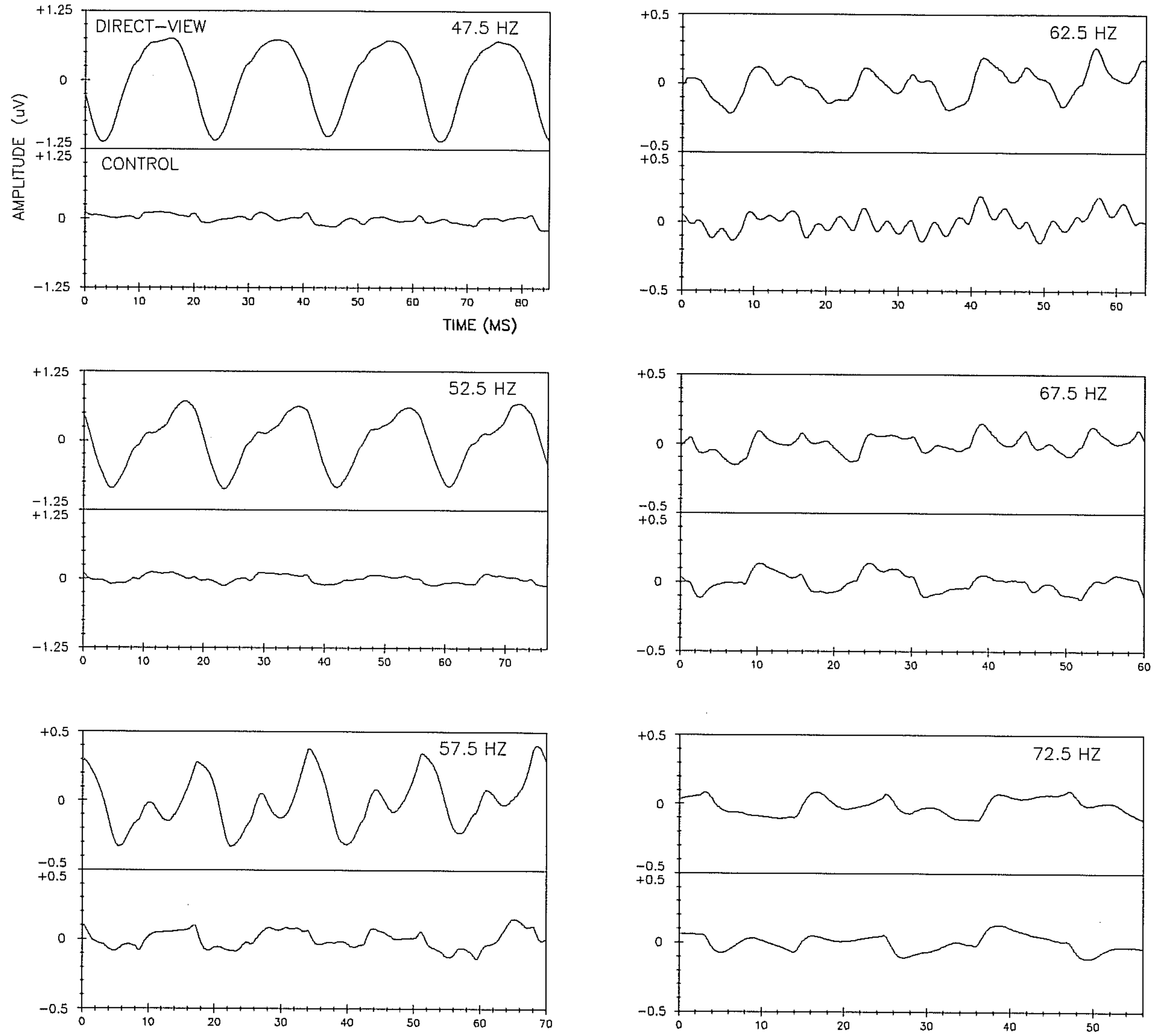


Figure 3. ERG responses to fluorescent light stimulus. ERG's for subject AMB are shown for mains frequencies ranging from 46.5 to 72.5 Hz. Upper trace is the ERG response to the direct view of the stimulus, whereas the lower trace is the background control run with fluorescent source occluded. The horizontal scale is adjusted in each graph so as to contain four periods of the mains supply. This is equivalent to four periods at the ballast or fundamental frequency, and eight periods of the first harmonic (the principal light oscillation frequency). See Tables 4 and 5 for harmonic analysis.

experimental conditions can be described as a sum of Fourier sinusoidal terms. The ERG response signal, y(t), is expressed as a sum over the same set of sinusoidal terms as the input signal, plus a noise function. Because the ERG response is less sensitive to higher than to lower frequencies, the sum usually only contains the fundamental and lower harmonics. The noise function here is not the more common random noise term, because of the possibility that the state of the system at any given time is somewhat dependent on its state at previous times. A commonplace example of this effect is that of an electrical circuit with a capacitance. This "memory" should not seriously affect the deterministic (sinusoidal) part of our fit, z(t), but it is important to consider this correlated noise when estimating the uncertainty in the fitted parameters. Proper uncertainty estimates are made under the assumption that the residual fitting error at any given time is independent of the error at any other time. If the system has a memory, the residuals from the deterministic fit, r(t) [where $r(t) = y(t) - z(t)$], are autocorrelated over time, and it is necessary to perform a time series analysis of these correlated residuals to get a final set of residuals, $\epsilon(t)$, that are independent over time (see equation 1 below). This procedure is needed to get a proper estimate of the uncertainties of the parameters of z(t).

Our analysis began by fitting a pilot set of the response data runs as just a sum of sinusoidal terms. Each data set consisted of 512 consecutive data points taken at time intervals of from 20 to 100 μs, with the shorter intervals corresponding to runs at higher frequencies. Examination of the residuals of these fits as a function of time indicated that they

Table 4. Subject AMB with fluorescent lamp stimulus: response amplitudes at the fundamental lamp frequency.[a]

Run	No. Trials Averaged	Amplitude (nV)		Phase Angle (°)	
		Mean value	Standard error	Mean value	Standard error
47.5 Hz-T	2,000	792.84	7.03	207	0.5
47.5 Hz-C	2,000	53.74	9.97	187	11
Difference	—	742.52	12.21	208	1
52.5 Hz-T	2,000	573.01	8.60	160	0.9
52.5 Hz-C	2,000	82.07	6.45	192	4.5
Difference	—	505.11	10.75	155	1.2
57.5 Hz-T	2,000	171.46	8.30	99.5	2.7
57.5 Hz-C	2,000	67.41	8.60	152	7.4
Difference	—	141.18	12.02	77	4.8
62.5 Hz-T	2,000	86.46	12.21	136	8.1
62.5 Hz-C	2,000	57.15	9.77	173	10.1
Difference	—	53.25	15.73	97	17
67.5 Hz-T	2,000	52.76	8.79	128	9.5
67.5 Hz-C	2,000	67.41	8.89	152	7.7
Difference	—	29.02	12.51	21	25
72.5 Hz-T	2,000	49.34	11.14	100	12.7
72.5 Hz-C	2,000	56.67	7.52	136	7.6
Difference	—	33.12	13.29	15	23

The Net Response Amplitudes Obtained by Using Equation 3 to Obtain the Difference Between Test and Control Conditions

Frequency	Amplitude	Standard Error	Z Score	p Value
47.5 Hz	742.52	12.21	61	0
52.5 Hz	505.11	10.75	47	8E-485
57.5 Hz	141.18	12.02	12	2E-32
62.5 Hz	53.25	15.73	3.4	0.0004
67.5 Hz	29.02	12.51	2.3	0.01
72.5 Hz	33.12	13.29	2.5	0.006

[a] "T" refers to the test condition (subject viewing the fluorescent lamp) and "C" to the control condition (ERG lens in eye but lamp covered by heavy black cloth). Units of the amplitude are in nanovolts (10^{-3} μV).

were highly autocorrelated. This autocorrelation could not be removed by adding any reasonable number of signal harmonics. However, we found that the residuals from the deterministic portion of the fits could be fitted with a lagged autoregression. In this procedure the residuals are treated as a new data set, and each datum point is fitted as a function of previous data points. The fit is described as a lagged autoregression because a fixed lag is used to determine which previous points are used for each fit. The correlation coefficients for the residuals from this lag fit are not significantly different from zero and as a group have a nonsignificant value of Q on the Box-Jenkins lack of fit test,[19] indicating that no further major improvements in the fit are possible. We used the lag model developed to fit the pilot subset of conditions as our model for all conditions. The form of the fits using both lagged and unlagged sinusoidal terms is as follows:

$$y(t) = z(t) + \sum_{j=1}^{m} B_j[y(t-j) - z(t-j)] + \epsilon(t) \quad (1)$$

where m is the maximum lag, t is the time index, which runs from 1 + m to 512, the B_j are the lag coefficients, the $\epsilon(t)$ are independent normally distributed random errors, and the z(t) are as given below:

$$z(t) = A_o + \sum_{i=1}^{n} A_{i1}\sin(\omega_i T) + A_{i2}\cos(\omega_i T)$$

$$= A_o + \sum_{i=1}^{n} A_i\sin(\omega_i T + \varphi_i) \quad (2)$$

where n is the total number of harmonics including power frequencies considered, T is the actual time corresponding to the time index t, the primary "deterministic" amplitudes A_i and the phase angles φ_i are unknowns, and the ω_i are the signal frequencies. Because we had established the form of the lag fit (equation 1) in our pilot analysis, we did not do a separate residual analysis for each experimental condition. Instead, we used a standard nonlinear curve-fitting package that in one pass estimates all the parameters and their uncertainties.[20]

In the actual fitting procedure we used the sum of the zero phase sine and cosine terms instead of the sine wave amplitude-phase form to make it easier to use the standard F test for the significance of an additional term.[20] After fitting, the coefficients were transformed back to the sinusoidal form. The standard propagation of error approximation using the first order Taylor's series expan-

TABLE 5. Subject AMB with fluorescent lamp stimulus: response amplitudes at the second harmonic of lamp driving frequency.[a]

Run	No. Trials Averaged	Amplitude (nV)		Phase Angle (°)	
		Mean value	Standard error	Mean value	Standard error
47.5 Hz-T	2,000	204.19	4.40	160	1.2
47.5 Hz-C	2,000	13.09	5.57	130	24
Difference	—	192.96	7.13	162	2.1
52.5 Hz-T	2,000	230.08	6.16	110	1.5
52.5 Hz-C	2,000	3.61	4.59	58	73
Difference	—	228.03	7.72	111	1.9
57.5 Hz-T	2,000	157.79	4.49	41	1.6
57.5 Hz-C	2,000	5.47	5.47	155	57
Difference	—	159.93	7.03	39	2.5
62.5 Hz-T	2,000	82.46	8.60	−39	5.9
62.5 Hz-C	2,000	6.25	6.64	−18	61
Difference	—	76.60	10.84	−40	8.1
67.5 Hz-T	2,000	35.66	5.76	−63	9.3
67.5 Hz-C	2,000	4.40	4.98	188	64
Difference	—	37.32	7.52	−57	12
72.5 Hz-T	2,000	27.65	8.11	245	17
72.5 Hz-C	2,000	2.25	4.40	192	112
Difference	—	26.38	9.18	250	20

The Net Response Amplitudes Obtained by Using Equation 3 to Obtain the Difference Between Test and Control Conditions

Frequency	Amplitude	Standard Error	Z Score	p Value
95 Hz	192.96	7.13	27	2E-163
105 Hz	228.03	7.72	30	8E-194
115 Hz	159.93	7.03	23	3E-114
125 Hz	76.60	10.84	7.1	7E-13
135 Hz	37.32	7.52	4.9	4E-07
145 Hz	26.38	9.18	2.9	0.002

[a] "T" refers to the test condition (subject viewing the fluorescent lamp) and "C" to the control condition (ERG lens in eye but lamp covered by heavy black cloth). Units of the amplitude are in nanovolts (10^{-3} μV).

sion was used to relate uncertainties in the sine and cosine terms to uncertainties in the sinusoidal amplitude and phase.[20]

The best lag fit that we had found in the pilot analysis when fitting residuals from the fit to the sinusoidal terms alone had lags of 1, 2, 4, and 8. We therefore did the sum in equation 1 over these four lags. If a coefficient, B_j, was not significantly different from zero it was dropped from the sum. Most fits had all four terms but, occasionally, the lag 4 term, and in one case, the lag 8 term, was dropped. This effect of dropping the lag terms in these cases was a slight change (usually an increase) in the uncertainty estimates of the remaining parameters. The effect was too small to change any of our conclusions regarding the significance of the signal.

We examined series based both on the powerline fundamental at 60 Hz, with odd harmonics only, and a series based on the fundamental of the signal frequency with both odd and even harmonics. The powerline terms were included to allow for a possible EMF from the mains wiring in the room or inadequate power supply shielding in the equipment. We restricted our fit to odd harmonics of the powerline fundamental because it is these that are most distorted by power supply filtering. The number of terms in the series for z(t), n, was determined by either adding or dropping terms one by one until there was no significant improvement in the fit. The signal fundamental and its harmonics were examined first, and then 60, 180, and 300 Hz were examined. None of the fits showed any significant contribution at 300 Hz. One fit suggested a significant 180 Hz contribution, but for reasons we describe below we did not keep this term in the final fit. A number of the rotating disc experimental runs showed a significant 60 Hz component, and these were kept. The largest signal harmonic that was examined was the fifth. It was significant for several of the fluorescent lamp experiments, but not for the other experiments. The fluorescent lamp experiment was run over a larger number of cycles than the other experiments and gave consistently cleaner results. We did not find any significant ERG response (see below) above the third harmonic.

Fits were performed for each of 48 different experimental conditions. With this large a number there is a high probability that some of the fits will accept some times as being significant when, in fact, they are not real (type II error). The underlying physiological mechanisms of the ERG response should be sufficiently similar so that the fits for the different experimental conditions should have the

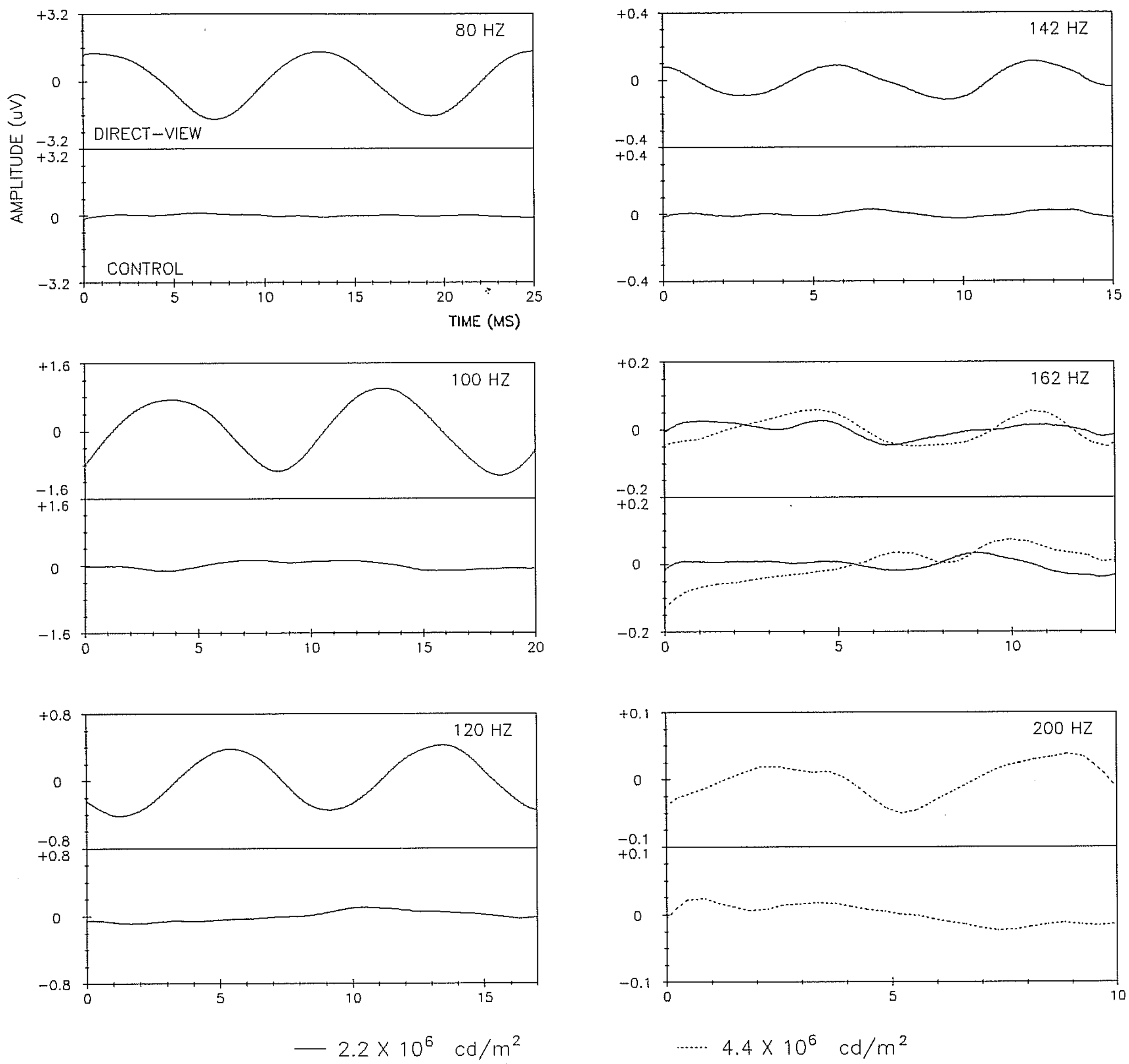


Figure 4. ERG responses to slide projector/rotating disc stimulus. ERG for subject AMB are shown for temporal modulations rates ranging from 80 to 200 Hz. The dc components have been subtracted from all traces with the direct view placed above the control condition. The time axis is adjusted as in Fig. 2.

same ensemble of terms. We used this as a constraint against adding excess terms to the fits, and to drop the one significant 180 Hz term mentioned above, as the latter was unique. Signal harmonics were also dropped if they were not significant in other fits, subject to the proviso that it is reasonable to have higher harmonics for the lower frequency runs. The effect of this pruning was similar to that of pruning the lag terms mentioned above, and again was too small to change any conclusions with respect to the significance of the results presented below.

In general, the addition of the lag terms made a difference of less than 0.5 SD's to the fitted values of the deterministic amplitudes and phases of the sinusoidal terms of equation 2, computed without the lag terms. As noted earlier, dropping lag terms which the fitting procedure claimed were not statistically significant made little difference to the values and uncertainties of the amplitudes and phases. However, dropping significant lag terms does make a difference. The magnitude of the uncertainty estimates for the amplitudes and phases increased by factors between 3 to 10 at the fundamental frequency of the analysis, and by smaller factors for higher harmonics. Even more important was the finding that the addition of the lag terms gave residuals that, as noted earlier, appear to be independent and normally distributed. This means that a standard t statistic can be used to establish confidence limits on the parameters A_i.

To test the first hypothesis that any control or any flicker signal is not due to noise, the confidence limits of the corresponding primary deterministic response amplitudes A_i were examined to see if they contained zero. The test of the second hypothesis

TABLE 6. Subject AMB with rotating disc stimulus: responses at the stimulus frequencies from the time series analysis of equation 1.[a]

Run	No. Trials Averaged	Amplitude (nV) Mean value	Amplitude (nV) Standard error	Phase Angle (°) Mean value	Phase Angle (°) Standard error
80 Hz-T	500	1503.11	28.82	62	1.1
80 Hz-C	500	53.74	17.59	252	19
100 Hz-T	521	904.70	69.86	−43	4.4
100 Hz-C	524	8.40	21.30	42	145
120 Hz-T	1,010	380.05	7.43	218	1.1
120 Hz-C	1,012	10.65	7.91	−41	43
142 Hz-T	2,000	92.82	7.33	147	4.5
142 Hz-C	2,000	17.78	4.30	115	13
162 Hz-T	4,000	18.76	4.98	214	15
162 Hz-C	4,000	20.22	6.55	239	18
162 Hz-HB-T	2,000	42.99	8.70	197	12
162 Hz-HB-C	2,000	9.28	6.74	173	44
200 Hz-HB-T	4,000	29.31	8.01	210	15
200 Hz-HB-C	4,000	4.20	3.22	111	43

The Difference Between Amplitudes for Test and Control Condition

Frequency	Amplitude Difference	Standard Error	Z Score	p Value
80 Hz	1449.38	33.71	43	3E-404
100 Hz	896.40	72.98	12.3	6E-35
120 Hz	369.31	10.84	34	2E-254
142 Hz	75.23	8.30	9.1	6E-20
162 Hz	−1.47	8.21	−0.18	0.57
162 Hz-HB	33.71	11.04	3.1	0.0011
200 Hz-HB	24.91	8.60	2.9	0.0018

[a] "T" refers to the test condition (subject viewing projector and rotating disc) and "C" refers to the control condition (ERG lens in eye but projector source blocked by opaque cardboard). The high brightness condition (HB) corresponds to a doubling of the luminance for the 162 and 200 Hz conditions compared to the linear frequencies.

that there is a real ERG response is that the confidence range of [A_i(test) − A_i(control)] does not contain zero.

Ideally the form of the fit (equation 1) will be consistent with a response that is at the same frequency as the frequency of the stimulus. In practice, the fit has very weak rejection of nearby frequencies because the data period is not significantly larger than the inverse test frequency. Thus, a finding of a significant signal indicates that there is a response to oscillating light, but does not guarantee that stimulus and response frequencies are the same.

VDT Study

Tables 2 and 3 present results from the VDT study and list the value of the amplitudes A_i, and the phases φ_i, as well as their standard errors for the six stimulus frequencies of subject RWR and the five stimulus frequencies of subject AMB, respectively. Subtracting the control condition values of A_i from the test condition values and using the standard errors listed showed that the response for the test condition is significantly larger than the response for the control condition at a level of $p <$ 0.1% for all frequencies up to 66 Hz for subject RWR and up to 76 Hz for subject AMB. At 81 Hz, for subject AMB the control condition gave a larger response than the test condition but this result is not statistically significant. Because the experiment was carried out with the test and control condition responses measured in immediate sequence, the comparison between the responses from these two conditions at the same frequency should be meaningful. On the other hand, comparing the values for the amplitudes A_i of equation 2 in the control runs at different frequencies is less meaningful because the ERG lens was sometimes removed for rest periods while the stimulus frequency was altered and then reinserted, in which case the resultant overall gain in the lens could possibly be different at the different frequencies. In addition, the studies for both subjects covered very narrow frequency ranges, so any biases in the amplitudes are magnified when trying to determine the resultant relative ERG sensitivities as a function of frequency. Exponential decay fits of amplitude vs. frequency were much noisier for these data than that for the other studies, and showed a more rapid decline in amplitude with frequency.

Fluorescent Lamp Study

Tables 4 and 5 present results for subject AMB for the fluorescent lamp study and list the value of A_i and φ_i for the fundamental and second harmonic. In the VDT and the sector disc experiments there were large uncertainties in the phase angles of the control runs (see Tables 2, 3, and 6), and we there-

Relative ERG sensitivity for the fluorescent lamp experiment versus frequency

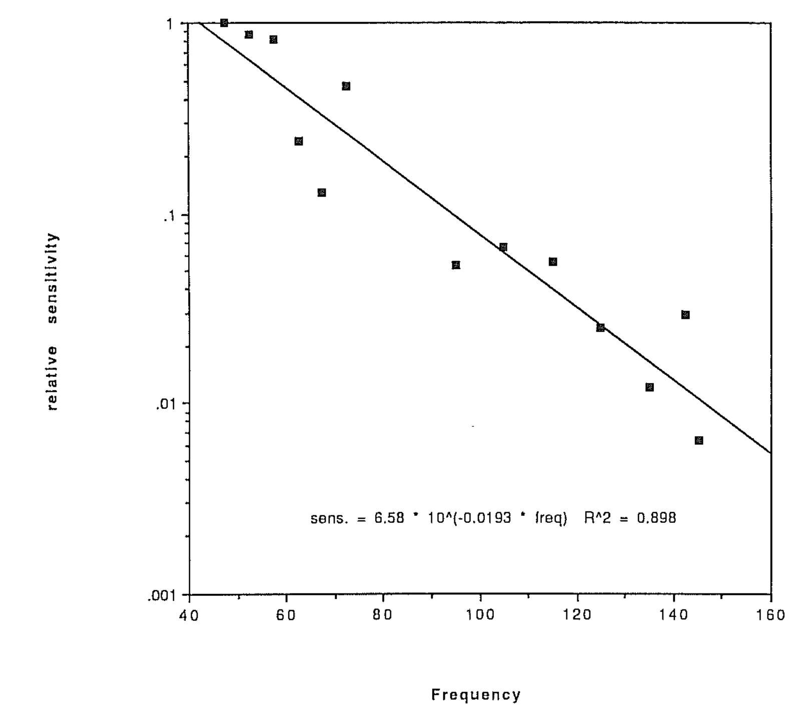


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Figure 5. The change in log relative ERG sensitivity for the fluorescent lamp data as a function of frequency of light oscillation with 100% light modulation for subject AMB. The data are fitted with a fall-off of the form log s = 0.8182 − 0.0193 f, where s is the relative sensitivity and f the frequency in Hertz. The ERG responses are normalized by the relative strengths of the fluorescent lamp Fourier components.

fore examined just the difference in the amplitudes of the test and control runs. In the fluorescent lamp study the uncertainties in the estimates of the phase angles of the fundamental were relatively small, and we therefore have shown the results for the parameters of the difference response, which is defined below as the solution to the equation:

$$A_{dif} \sin(wt + \varphi_{dif}) = A_{test} (\sin wt + \varphi_{test}) - A_{cont} \sin(wt + \varphi_{cont}) \quad (3)$$

The standard error for the difference response parameters was again calculated by the approximate method described earlier.[20] However, for the second harmonic the small size of the amplitudes for the control conditions relative to those for the test conditions made the results insensitive to this type of analysis. Instead we found it convenient to use equation 3. The statistical analysis shown in Tables 4 and 5 indicates that the difference of the response amplitudes are significant at the $p < 1\%$ level for all frequencies measured. However, if the amplitudes for the test and control conditions are simply differenced for the fundamental, as was done for the VDT study, these differences for the ballast frequency at 62.5, 67.5, and 72.5 Hz would not have shown significance (Table 4). Even without using equation 3, which takes into account the possible differences due to phase, all the second harmonics remain significant, which suggests that there could be a response to the fundamental and hence the difference signal analysis of equation 3 is more appropriate.

The relative amplitudes of the harmonics of the fluorescent lamps can be used to estimate how the ERG sensitivity decays with frequency. The values in Tables 4 and 5 were scaled by the input power ratios given in Table 1, and a ratio of amplitudes was taken. This method avoids the problem of possible gain changes between runs that was discussed earlier in the VDT runs. These values show a rough fit to an exponential decay model as a function of frequency that gives a 50% drop in sensitivity every 15 ± 3.5 Hz as shown in Fig. 5. A check by a specific calculation of the decays using the values of Tables 4 and 5 directly is reasonably consistent with the smooth slope shown in Fig. 5. This decay function has approximately the same slope as previously obtained at lower frequencies to a maximum of 63 Hz for the ERG response to the modulation of an oscillating grating pattern.[13]

Sector Disc Study

The results of our statistical analysis applied to the sector disc results are shown in Table 6. This analysis shows that a statistically significant ERG response ($p < 0.1\%$) was observed at all 6 test frequencies, including the highest at 200 Hz (except for the 162 Hz reduced brightness condition).

The relative amplitudes of the ERG responses for the sector disc experiment at the different test frequencies are subject to the same uncertainties as in the VDT experiment. However, like the fluorescent lamp experiment, the frequency range covered is much larger, and therefore estimates of the change in sensitivity of the ERG response with frequency are less subject to error. We found a reasonably good fit to an exponential decay model with a 50% drop in sensitivity every 11 Hz, as shown in Fig. 6, which is within the range found for the fluorescent lamp data (Fig. 5).

In determining the decreasing sensitivity of the ERG response with increasing frequency as displayed in Figs. 5 and 6, the data were plotted as log ERG sensitivity vs. frequency. (The data can also be plotted with log ERG sensitivity vs. log frequency with the goodness of fit essentially unchanged. However, in this case the fluorescent lamp and sector disc experiments yield two distinct slopes, whereas the two slopes are approximately the same when the abscissa is simply frequency.) The data from Figs. 5 and 6 can be combined with the previous lower frequency study[13] and psychophysical data[5] to show the decaying sensitivity to flicker over the full frequency range of measured responses and are shown in Fig. 7.

An interesting result concerning the phase is given in Table 6 (sector disc stimulus), which is based on a simple model of the ERG signal resulting from the light stimulus, but with a fixed time lag τ. If the measured phases φ_i at the various frequencies given in Table 6 are due to a fixed time lag τ, then these must be related by the equation:

$$\varphi_i = 2\pi f_i \tau - 2\pi(n_i + \varphi_o) \qquad (4)$$

where f_i are the test frequencies, n_i are positive or negative integers, φ_o is an unknown constant phase angle determined by the response of the Nicolet system, and τ is the physiological time delay of the ERG response. For any fixed set of n_i this is a linear regression equation. We fitted the results for the six experimental conditions in Table 6 that gave statistically significant amplitudes. We used the first two phases to determine a consistent set of n_i (0, 0, −1, −1, −2). A linear least-square fit to the adjusted phases had a correlation coefficient of 0.99, which is statistically significant at the 0.2% level after correcting the degrees of freedom for our use of the data to select the n_i. This procedure estimates a time delay of 14 ms, which is consistent with expectations based on the latency of the early receptor potential.[21]

A similar analysis for a time delay applied to the VDT data (Tables 2 and 3), especially that of subject AMB, was much noisier. No consistent time delay was found for subject AMB. For subject RWR a very "noisy" fit estimated a time delay of 22.5 ms. Because these data show a much higher proportion of EMF to visual signal they are not as reliable an estimator of the time delay as the rotating disc data.

For the fluorescent lamp data (Tables 4 and 5) where the response generally indicates the presence of two prominent frequencies and because the ERG is likely to be a nonlinear response with possible mode mixing, we do not expect a simple analysis of phase by a single time lag factor to be applicable. Nevertheless, there is a good fit using equation 4 with a high linear correlation coefficient for both the fundamental and the second harmonic. The fitted time lag is 16 ms for the second harmonic,

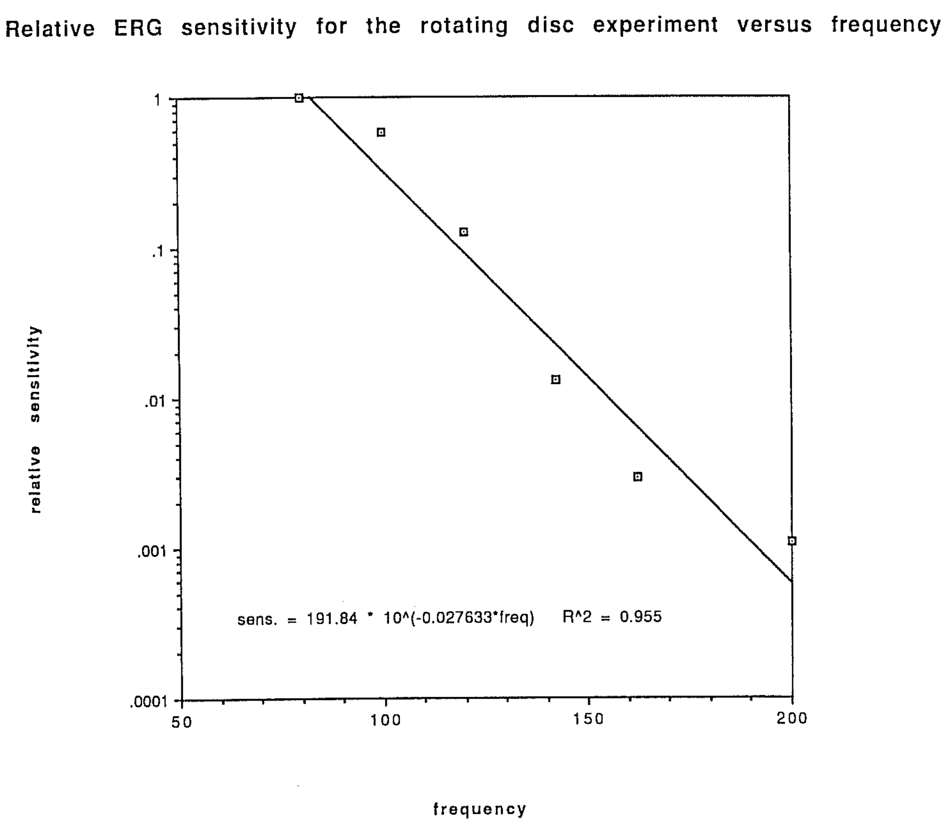

Figure 6. The change in log relative ERG sensitivity for the rotating disc experiments as a function of frequency of light oscillation with 100% light modulation. The data are fitted with a fall-off of the form log s = 2.2829 − 0.0276 f, where s is the relative sensitivty and f the frequency in Hertz.

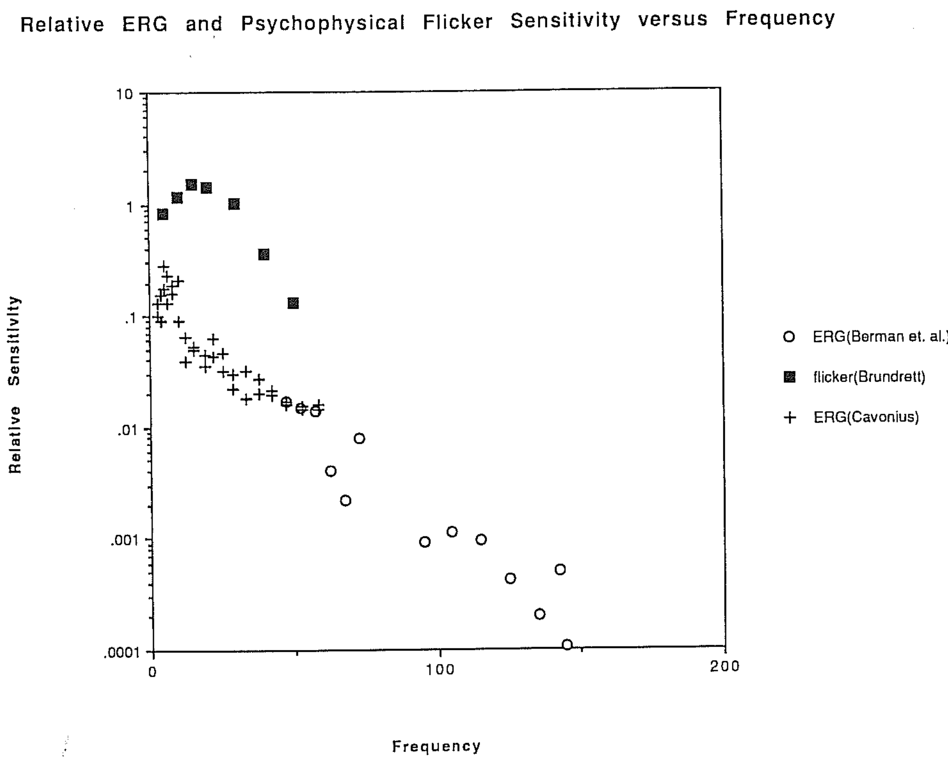

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Figure 7. The change in log relative ERG sensitivity for the experiments reported here along with the results reported by Cavonius and Sternheim[13] normalized to equal our results at 45 Hz. The relative threshold of perceived flicker response of Brundrett[5] is shown on the same graph.

and 30 ms for the fundamental. Because of the possible nonlinear interactions between the two frequency channels the interpretation of these "time delays" is uncertain.

Photovoltaic (PV) Contamination

It has been claimed[11,22] that when extensive signal-averaging is used in measurements of low-amplitude signals, it is possible for the ERG signal to be contaminated by a PV reaction in the electrode itself. To test the hypothesis that the responses we found were not due to a PV effect, the Burian-Allen electrode was placed in a saline solution and the signal was measured by the Nicolet system when the electrode was exposed to the rotating sector disc stimulus. We observed a PV signal (see Fig. 8) whose amplitude and phase for a fixed luminance appears to be constant over the 80 to 200 Hz frequency range used in our experiments. When the frequency is fixed, and the luminance of the source increased, the amplitude of the PV signal increased.

It is likely that the origin of this PV signal is related to the electrochemical potential that is present because of the dissimilar metals that compose the ERG electrodes.

A physical analysis of the Burian-Allen bipolar ERG electrode indicates that the ring electrode contains only pure silver, whereas the speculum consists of "German" silver, an alloy. Because the active electrode materials are dissimilar, there is an electrochemical or "battery" effect when the lens is in contact with a conductive medium, such as the human tear film. The resulting dc potential can then be modulated directly by light, hence resulting in PV contamination of the ERG signal. The modulation results because photons from the stimulus light source have a few electron volts in energy and consequently have the capability of ejecting electrons from the metal electrodes especially as their work function is reduced in saline solution. The resultant small variation in current flow would appear as a light-induced synchronous modulation of the ERG signal.

These effects are easily simulated by immersing the Burian-Allen lens into a saline solution. A dc potential of approximately ⅓ V can be measured across the two active electrodes, and a robust PV signal is produced when the lens is exposed to the flickering light from our rotating sector disc stimulus. Similarly, immersion of a stainless steel disc and copper disc into a saline solution produces a dc potential and a sensitivity to light. But when two discs of the same material are placed in the saline solution, both the dc potential and PV modulation effect disappear. This suggests that a different Burian-Allen lens, in which the active electrodes are made of identical material, would eliminate or substantially reduce PV contamination of the ERG signal without diminishing sensitivity to the physiological signal. Such an electrode arrangement may prove of considerable value in the measurement of weak ERG signals.

The absolute amplitude of the PV signal, as determined with the electrode in saline solution, cannot be compared meaningfully with the amplitude of the total ERG and PV signal measured when the electrode was worn by the subject. This is because of the differences in electrical impedance

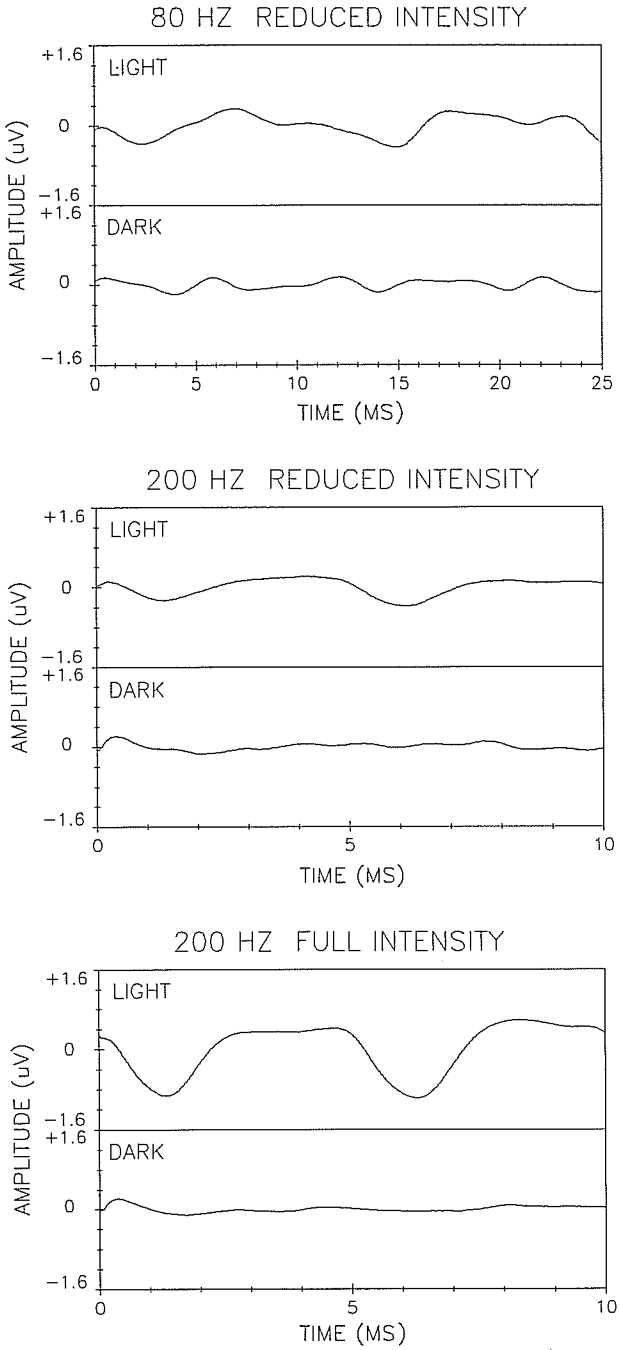

Figure 8. Frequency and intensity dependence of the PV response. The response of the Burian-Allen electrode when placed in saline solution and exposed to the rotating sector disc stimulus (upper trace) or occluded from light source (lower trace). The dc component has been removed from all traces. The time axis is different for the two frequencies such that the response for two cycles of the stimulus is presented.

of the surrounding mediums and the greater exposed area of the electrode when in the saline solution. However, given that the PV signal is independent of frequency, the change in ERG voltage response with frequency condition can provide a valid means for assessing PV contamination. In the rotating disc experiment, the ERG response exhibited a decrease in amplitude by a factor of approximately 2 for each successive increase in frequency. Thus, the amplitude at 200 Hz was approximately 1/32 the amplitude at 80 Hz (even with the 2 times greater luminance used at the highest 2 frequencies). Having found the amplitude of the PV signal to be independent of frequency, we conclude that we have demonstrated a significant ERG response in subject AMB to at least the second highest frequency tested, 162 Hz. Similarly the test ERG responses to the fluorescent lamp signal show a systematic decrease in amplitude as the frequency of lamp operation increases. Because the PV response does not decrease with increasing frequency, it will be no greater in magnitude than the weakest signal obtained, which was at the 200 Hz stimulus frequency. Similarly, we conclude that up to at least the second highest frequency, our measured ERG response to fluorescent lighting is due not entirely to PV contamination.

Furthermore, because in the VDT experiment the response disappeared entirely at the high refresh rates, we believe that there was no significant PV contribution to the response in the VDT experiments.

We have also examined the possibility that the presence of the large dc electrochemical potential in the Burian-Allen lens could reduce the ability of the Nicolet system to provide accurate averaging of the time-dependent component. To test this hypothesis we gave the Nicolet a signal with a periodic sine wave of 1.0 μV amplitude in the presence of a series of dc potentials increasing from a base amount of 0.25 V. The Nicolet system provided a faithful reproduction of the sinusoidal signal up to a dc voltage of 1.193, which is considerably higher than the 0.3 V of electrochemical potential obtained with the Burian-Allen lens. Thus, we conclude that the measured biological responses are not affected by the dc electrochemical potential and, furthermore, that a lens system with electrodes of equal material should be more desirable.

DISCUSSION

Earlier studies of human ERG responses to high frequency stimuli[12,13] have reported clear ERG signals at 63 Hz, but there are no indications of whether responses were obtained at higher frequencies. Their experiments (approximately 20° field grating stimulus presented in Maxwellian view) were concerned primarily with the amplitude of the temporal modulation and the stimulus required to achieve a prescribed voltage in the ERG signal which was averaged for a few seconds of exposure. There were significant differences between the stimulus conditions for our VDT study and those pertaining to previous experiments.[12,13] The area of our visual stimulus was smaller (12° compared to 20°), and the mean retinal illuminance from our VDT stimulus was less than that of their grating display (approximately 300 Td compared to 2000 and 3000 Td), even though there was relatively close similarity between the peak retinal illuminance from our display (1650 Td pixel centers) to their display fields. Because stimuli of lower luminance and smaller area produce weaker responses, it became necessary for us to use considerably more signal averaging in order to demonstrate that there is indeed a measurable ERG signal generated in response to the temporal modulation presented by a VDT screen. In the review article on neuroelectric events,[15] a figure attributed to Riggs et al. is presented, showing human ERG responses to repetitive flashes up to 110 and 125 Hz with the peak luminances approximately 30,000 cd/m^2. There is no information presented about the field of view, duty cycle, experimental controls, or statistical analyses. Riggs' finding that ERG signals could be obtained from stimuli oscillating at frequencies substantially higher than the perceptual CFF has been largely ignored, but it is supported and extended by our results which show that a measurable but gradually decreasing ERG signal is obtained from stimuli oscillating at rates up to 200 Hz. Our ERG results are consistent with the absence of any high-frequency threshold for fusion in retinal response. It is possible that responses continue at higher frequencies and could be measured with a combination of more sensitive detection and longer periods of data averaging.

Because our data show a gradually decreasing ERG response as frequency increases and have phase lags consistent with retinal electrophysiology, we believe our measurements reflect neuronal activity in the retina. However, it is possible that these weak signals at the higher frequencies are emanating from some other structure(s) of the eye. This question could possibly be resolved by examining the ERG responses in subjects with retinal diseases, such as retinitis pigmentosa, that produce a reduction or extinction of the normal clinical ERG. However, to test at the higher frequencies, high luminance levels become necessary and this could present a hazard to subjects with retinitis pigmentosa or similar retinal diseases.

We have shown that synchronous ERG responses to periodic light stimuli can be elicited in humans viewing a VDT with its text luminance and contrast conditions somewhat typical of the workplace environment (but room ambient light absent). In addition, we have obtained synchronous ERG responses to fluorescent lamps with their dominant frequency as high as 145 Hz and we have also found responses to a high intensity source at frequencies even higher than have been elicited in electrophysiological responses in cat studies. Eysel and Burandt[9] have shown that cat retinal responses to light modulation at high frequencies on the order 100 Hz are accompanied by similar responses further in the visual system pathway at the LGN. We may speculate that there could be a comparable LGN response to these high frequencies in our human subjects and ask whether any sensory or motor vision function could be affected by the presence of a retinal response to high-frequency stimulation. Future studies would be required to answer this question as well as the question of whether retinal responses to flicker are relevant to the headaches and eyestrain that were found to be associated with flicker from fluorescent lighting.[23] In this context, the relevance of our fluorescent lamp results that show comparable ERG responses to the first and second harmonics should be considered inasmuch as commonly used fluorescent lamps often produce a small component of light oscillation at the mains frequency (first harmonic). It would also be of interest to examine the ERG responses of people who report increased sensitivity to flicker to determine whether they have larger ERG amplitudes at supra perceptual CFF's or whether their ERG response shows a higher electrophysiological CFF.

Wilkins[17] has presented some evidence that flicker rates higher than the perceptual CFF can affect accuracy of saccadic eye movements. It would be of further interest to compare directly the effect of flickering light and steady-state stimuli on saccadic eye movement. Certainly, if these demonstrated ERG responses to periodic light stimuli could be shown to be correlated with decreased visual function or to visual discomfort there would be merit in modifying both new and existing equipment, even though such modifications may not be trivial.

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