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SMOOTH PURSUIT EYE MOVEMENTS IN RESPONSE TO UNPREDICTABLE TARGET WAVEFORMS

A. TERRY BAHILL, MICHAEL J. IANDOLO and B. TODD TROOST

Neurological Control Systems Laboratory: Biomedical Engineering Program, Department of Electrical Engineering, Carnegie-Mellon University and Neurology Service, Veterans Administration Medical Center; Department of Neurology, University of Pittsburgh Medical School; Pittsburgh, PA 15213, U.S.A.

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Abstract—Humans track smoothly moving objects with a combination of saccadic and smooth pursuit eye movements, called dual mode tracking. A pseudo random ternary sequence was used to generate an unpredictable target motion that had linear ramps of random velocity and duration. This aperiodic waveform eliminated the subject's ability to predict target motion. Saccades were removed from these records leaving only smooth pursuit eye movements, called single mode tracking. Transfer functions were computed for both single and dual mode tracking. The difference in the transfer functions between 0.7 and 1.0 Hz is an indication of the quality of the smooth pursuit tracking which decreases with increasing target waveform bandwidth and with fatigue. The coherence function provides another quantitative measure of smooth pursuit tracking.

INTRODUCTION

Humans use four eye movement control systems; vestibulo–ocular, vergence, saccadic and smooth pursuit. Although these subsystems interact, they may be selectively affected by disease or drugs. We have, therefore, tried to isolate and study the fundamental aspects of one of these systems: the smooth pursuit system. Holding the head fixed eliminates the vestibulo–ocular system, while keeping the target at a uniform distance from the subject eliminates the vergence system. In order to study the fundamental smooth pursuit system, two factors still have to be eliminated: the predictive capability of the smooth pursuit system and the effects of the saccadic system. The predictive capability is eliminated by the choice of the target waveform, and the effects of the saccadic system are eliminated with the data analysis programs.

There are differences between tracking periodic and nonperiodic targets. A periodic sinusoidally moving target is the easiest waveform to track; tracking unpredictable waveforms is harder. When tracking a periodic stimulus, the accuracy of a saccade to a new target is better in the beginning, before prediction has begun, than after tracking several cycles of the target movement (Miller, 1980). Smooth pursuit eye velocity is dependent on stimulus contrast for unpredictable target motions, but not for predictable motions (Haegerstrom-Portnoy and Brown, 1979). Barbiturates decrement smooth pursuit tracking of periodic targets at much lower doses than they decrement smooth tracking of nonperiodic targets (personal communication Michael J. Morgan). To eliminate the effects of the human predictive capability we have used unpredictable target motions. There are many choices for unpredictable target waveforms, e.g. the sum of several nonharmonically related sinusoids (Stark *et al.*, 1962), and gaussian white noise (Dallos and Jones, 1963; Shirachi *et al.*, 1978). Our new unpredictable target waveform is easier to implement, easier for the subject to track, and allows more efficient data analysis programs to be used.

The smooth pursuit system is disrupted more than the saccadic system by alcohol, drugs and fatigue (Rashbass, 1961; Wilkinson *et al.*, 1974; Flom *et al.*, 1976; Baloh *et al.*, 1976; Norris, 1971). A variety of central nervous system diseases may show smooth pursuit defects as an early ocular motor system abnormality (Zee *et al.*, 1976; Troost and Daroff, 1977). Our data analysis programs eliminate the effects of the saccadic system and allow us to study the smooth pursuit system by itself.

There is no simple method for quantifying smooth pursuit performance. The degradation of the saccadic system is easily quantified by plotting peak velocity and duration as functions of saccadic magnitude, independent of target movement parameters. Fatigue and disease will decrease the peak velocities and increase the durations (Bahill and Stark, 1975; Troost and Daroff, 1977). However, a similar technique will not work for the smooth pursuit system because the eye velocity and duration of movement are directly dependent upon the target movement.

It would be possible to compute the ratio of target velocity to eye velocity at several sample points along a record (Troost *et al.*, 1972; Baloh *et al.*, 1976; Sharpe and Sylvester, 1978). However, the ratio is not unity for normals: there are usually velocity errors. Furthermore, if the sampling took place during a position correcting saccade, then the average would be substantially altered.

Of course if there is no smooth pursuit function at all, then it is quite easy to see that the tracking is entirely saccadic. If there is only a little smooth pursuit ability, then the resulting tracking would be mostly saccadic. This makes it natural to suggest that performance of the smooth pursuit system could be quantified by an inverse measure of the number and size of the saccades in a record. Such a measure has been previously defined (Yamazaki and Ishikawa, 1973).

These time domain analyses throw away large amounts of data. The velocity sampling techniques typically use one sample point out of each 100 msec. The saccade counting techniques only use the saccadic intervals, which typically constitute less than 10% of the data.

Frequency domain techniques may allow a greater portion of the data to be utilized. A frequency domain approach for studying eye movements has been used previously (Wolfe *et al.*, 1978). However, they only used predictable sinusoids, which meant that their subject's tracking responses were based upon use of their internal model. Thus they were studying a larger more complicated system than the one we are reporting upon here.

We are reporting on the use of nopredictable target waveforms and frequency domain analysis techniques for the quantitative study of human smooth pursuit eye movements.

METHODS

Target waveforms were generated with a digital algorithm on a LSI-11 minicomputer and were converted into analog voltages with a 10 bit digital to analog converter at 2000 Hz. The band limited gaussian white noise waveform was generated with a noise source and stored on an FM tape.

The target was a small (3 mm dia.) red laser dot projected on a ganzfeld 57.3 cm from the subject. Target voltages from the computer and the tape recorder moved a galvanometer which had a small mirror attached. Movement of the mirror, due to the random voltage outputs, deflected a laser beam to produce the horizontally moving dot on the screen. Bandwidths for the galvanometers and d.c. amplifiers exceeded 50 Hz. Subjects viewed the target binocularly in a dimly illuminated room.

Eye movements were measured by means of standard photoelectric techniques (Bahill *et al.*, 1975b). The linear range for the measurement of horizontal eye movements extended $\pm 10°$ from primary position. This low noise system allows recording of saccades as small as 3′ of arc. The target movement and the movement of the eyes were sampled at 60 Hz and stored on a disk in the laboratory's PDP-11/34 computer. All subsequent analysis was performed using the PDP 11/34 computer. Informed consent was obtained after the experiment and the equipment was explained to the subject.

Target movements were within $\pm 10°$ of primary position because most naturally occurring eye movements are within this range (Bahill *et al.*, 1975a). Larger target displacements require coordinated head and eye movements. Target velocities greater than 40 deg/sec were not used because humans cannot pursue small dots moving unpredictably at faster speeds (Young and Stark, 1963). The targets were designed to have constant velocity regions because the input to the smooth pursuit system is presumably target velocity. The ability to track targets with nonconstant velocities involves other higher level processes that we wished to eliminate from the system under study. We wanted the target to have properties approximating white noise to facilitate the frequency domain analysis and allow short test runs which would reduce the

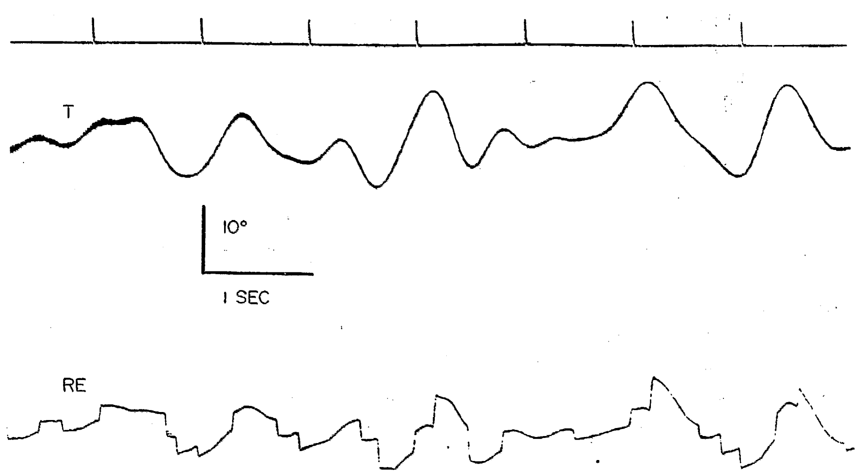

Fig. 1. Target (T) and right eye (RE) position as functions of time for bandlimited (0 to 0.8 Hz) Gaussian white noise. This type of target motion is difficult to follow as indicated by the large number of saccades. Upward deflections represent rightward movements in all figures.

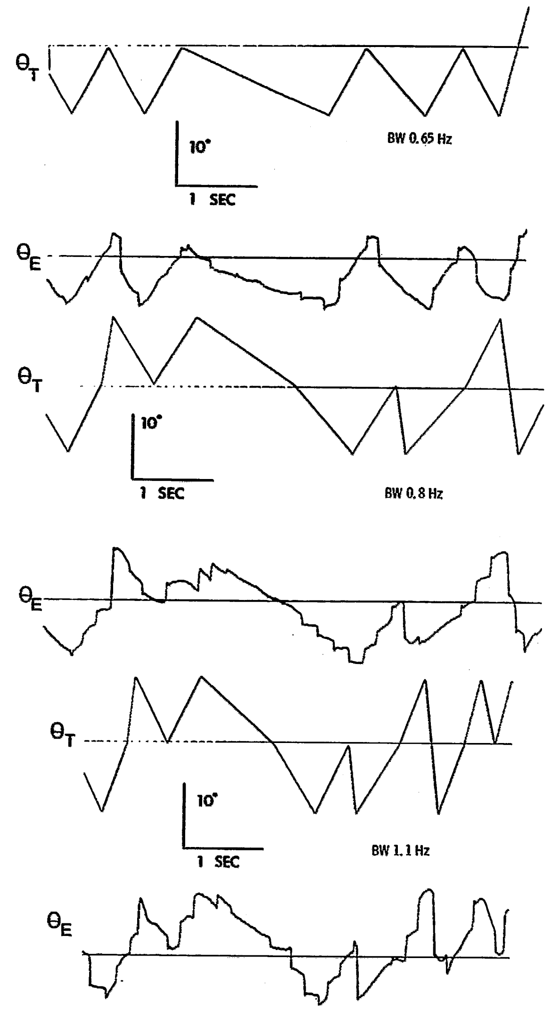

Fig. 2. Target (θ_T) and eye (θ_E) positions as functions of time for unpredictable pseudorandom target waveforms with bandwidths of 0.65 Hz (top), 0.8 Hz (middle), and 1.1 Hz (bottom).

effects of fatigue. Following calibration a 3 min test was performed. The subject was allowed to rest for 3 min and the test sequence was repeated.

A variety of target waveforms were initially explored. We tried bandlimited (0 to 0.8 Hz) Gaussian white noise and found very poor smooth pursuit tracking (Fig. 1). The subjects complained that it was very confusing to watch. This was the most difficult target waveform used. A target movement was needed that would be nonpredictable, yet still give some clues to the subject.

Another target movement initially explored was based on a pseudorandom binary sequence. Basically a signal with only two possible values; the time in each of these states is random. Such a generator can be implemented using a shift register with an exclusive OR gate in the feedback pathway (Peterson, 1961; Golomb, 1967; Marmarelis and Marmarelis, 1978). It is called pseudorandom because the series repeats itself; in our test protocol every 90 sec. The classical method of using this sequence is to integrate the sequence to yield constant velocity ramps of random duration. The problem with this technique is that only a single velocity, either to the right or the left, is produced. Since the input to the smooth pursuit system is velocity, a number of test velocities should be employed to characterize the system.

The target movement finally used was based on a pseudorandom ternary sequence; basically a signal with three possible values. This signal does not introduce artifacts into the computed results as occurs with a pseudorandom binary sequence (Swerup, 1978). The ternary signal was filtered to generate a series of ramps that were random in velocity and duration. A clue that the subject received was the fact that the target would only change velocity in the center or at the ends of the display. This hint was necessary to avoid making our stimulus as confusing as the Gaussian white noise. The final waveform is shown in Fig. 2.

The target waveform should have properties approximating white noise. Practical considerations require that bandlimited noise be used. Normal engineering practice is to use a noise bandwidth that is ten times as large as the bandwidth of the system under study. That was not feasible for this study because the system performance depended upon the signal bandwidth. A large bandwidth target was confusing and difficult to track. The resulting eye movements had little power in the frequency region of interest and the confidence intervals of the estimated transfer functions were larger. The target waveform that gave the best results was 3dB down at 0.8 Hz.

The target and eye movement data were low pass filtered, and were subsequently digitized at a 60 Hz sampling rate. This digital data was filtered with a Hamming window. The single mode tracking record was formed by removal of the saccades. Then a fast Fourier transform (FFT) was taken of the target, dual mode, and single mode records to yield frequency domain data. The cross-spectral density was then computed as

$$G_{xy}(f) = \frac{1}{N} X_N^*(f) Y_N(f)$$

where $X_N^*(f)$ is the Fourier transform of the complex conjugate of the input time function and $Y_N(f)$ is the Fourier transform of the output time function. The transfer functions were calculated via the Weiner–Hopf relationship.

$$H(f) = \frac{G_{xy}(f)}{G_x(f)}$$

where $H(f)$ = the transfer function, $G_{xy}(f)$ = the cross power spectral density and $G_x(f)$ = the input (target) power spectral density.

The coherence function was calculated with

$$\gamma^2(f) = \frac{[G_{xy}(f)]^2}{G_x(f)G_y(f)}$$

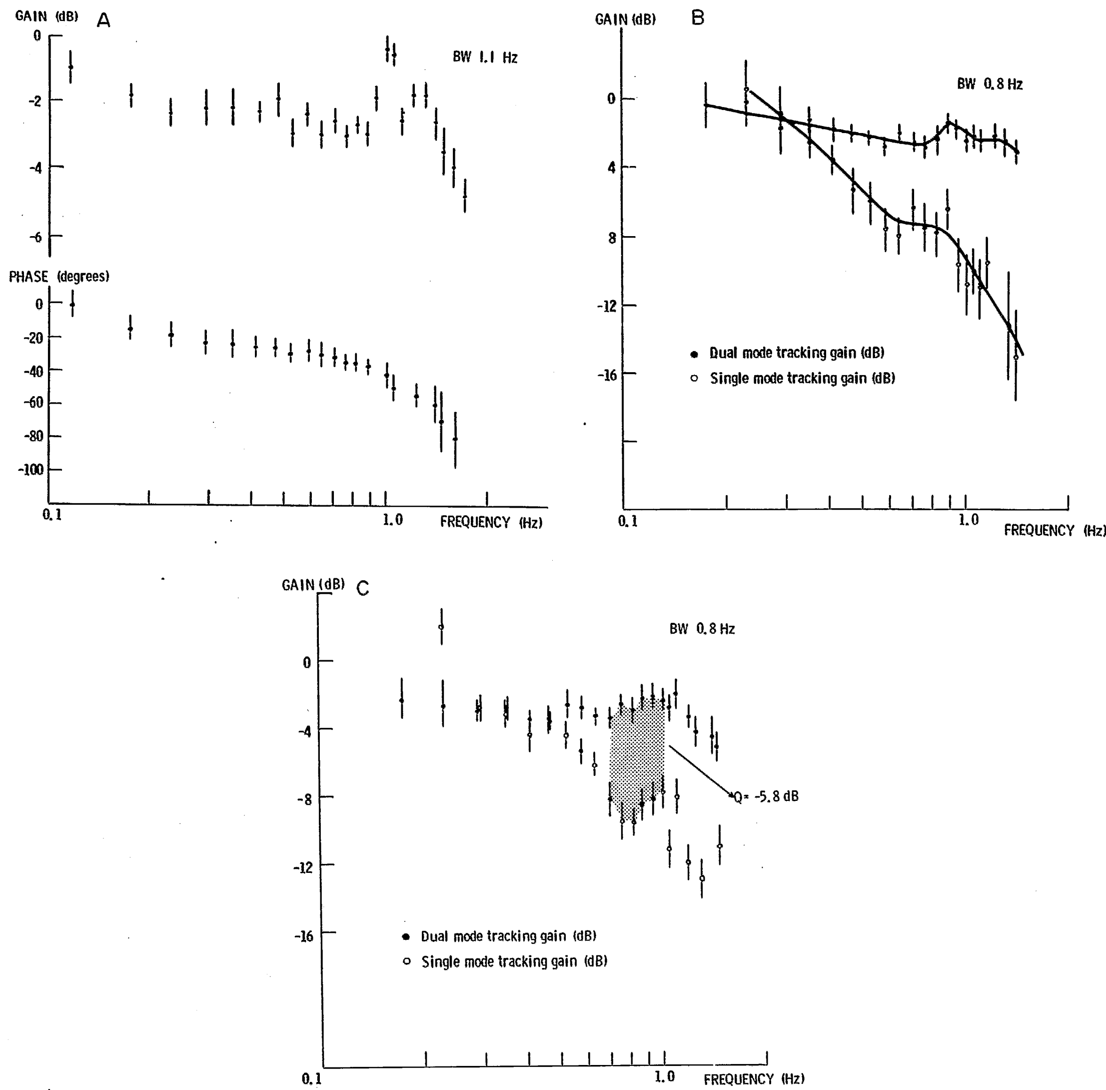

Fig. 3. Dual mode (smooth pursuit and saccades) transfer function (A) for a subject tracking the 1.1 Hz bandwidth pseudorandom target waveform of Fig. 2. (B and C) dual mode (uppermost curve at high frequencies) and single mode (lower curve at high frequencies) transfer functions for subjects tracking the 0.8 Hz bandwidth target waveform of Fig. 2. The data of the top two figures are for the same subject. The area between the curves for frequencies 0.7 to 1.0 Hz, the stippled area in the lower figure, is the quality factor, Q. Each of our transfer functions was computed from 35 min of artifact free data gathered on 5 separate days. The bars are 95% confidence intervals.

where $G_y(f)$ is the power spectral density of the output (the eye movement).

Figure 3a shows the gain and phase relationships for tracking the small dot of light driven with the nonpredictable waveform of Fig. 2. The bars indicate 95% confidence intervals. These confidence intervals were derived using the coherence function in conjunction with the number of data points at each frequency. As expected, our data matched the data from the literature (Stark *et al.*, 1962; Dallos and Jones, 1963). However, these data represent the transfer functions for the combined smooth pursuit and saccadic eye movement systems. We only wished to study the smooth pursuit system.

We therefore took the dual mode tracking records (smooth pursuit and saccades) and removed all saccades (Fig. 4) thus leaving only the smooth pursuit portions. The resulting record has been termed single mode tracking (Yasui, 1974).

Our algorithm for removing saccades (Fig. 4) necessitated the computation of the eye velocity trace. We computed eye velocity as a function of time and set a threshold at 50 deg/sec. This was higher than any expected smooth pursuit movements (target velocities were always less than 40 deg/sec) and would easily detect all saccades of 1° or larger. Whenever the eye velocity exceeded 50 deg/sec we calculated the peak-velocity–magnitude–duration parameters for the

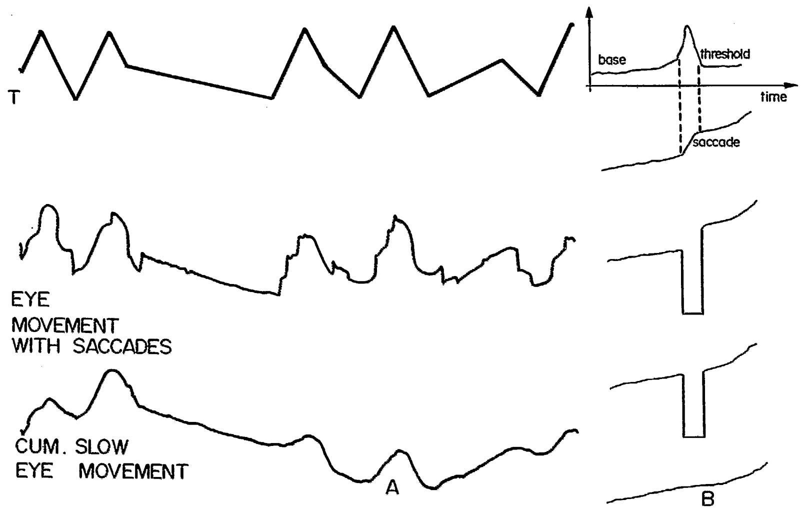

Fig. 4. Target position (top) and eye position (middle) as functions of time. The eye tracking shows contributions of both the smooth pursuit and the saccadic systems; dual mode tracking. The saccades are removed from the dual mode record to yield the single mode tracking record (bottom) which has only smooth pursuit eye movements. B. To form the single mode tracking record the eye velocity trace (top) is monitored. If the velocity exceeds a specified threshold, then an event has occurred. If the peak-velocity–magnitude–duration parameters of this event match normalitive data, then the event is called a saccade. It is removed from the record and replaced with a marker. The offset produced by the saccade is removed and the gap is filled by linear interpolation to yield the single mode tracking record (bottom).

event, the main sequence parameters (Bahill and Stark, 1979). If the parameters matched those of a normal saccade for that particular instrumentation bandwidth we called the event a saccade and proceeded to remove it from the data. If the parameters did not match the main sequence data, the event was not a saccade and the whole record was discarded. If the event was a saccade, then the displacement caused by the saccade was removed from the record and the gap was bridged with a line having the same average slope as the eye position record immediately before the saccade. We then calculated the transfer function of the single mode tracking record.

RESULTS

Figures 3b and 3c show the comparison of the single mode and dual mode transfer functions for two subjects. The dual mode transfer function has a higher gain than the single mode transfer function in the frequency region around 1 Hz. Saccadic eye movements are faster than smooth pursuit and therefore have more energy at higher frequencies. The difference between the two transfer functions is an indication of how much of the tracking is due to the saccadic system and how much is due to the smooth pursuit system. If the tracking were predominately saccadic the difference would be large; conversely if there were no saccades there would be no difference. In order to quantify this difference we have defined the *quality* of the smooth pursuit tracking to be

$$Q = 10 \log_{10} \sum_{f_i} \frac{H_S(f_i)}{H_D(f_i)}$$

where $f_i = 0.7, 0.75, 0.8, 0.85, 0.9, 0.95, 1.0$ Hz. $H_S(f)$ is the single mode transfer function and $H_D(f)$ is the dual mode transfer function. Q is the area between the dual mode and single mode transfer functions between 0.7 and 1.0 Hz, as shown in Fig. 3c. The Q factors for these data are -5.9 dB for (b), and -5.8 dB for (c). Two other subjects had Q factors of -4.4 dB and -5.4 dB.

The quality of the smooth pursuit tracking depended upon the stimulus bandwidth. We computed the power spectrum of the target waveform and defined the bandwidth to be from 0 Hz to the frequency where the power dropped 3 dB. As the stimulus bandwidth became larger the target movement reversals occured closer together, and the smooth pursuit tracking deteriorated. In Fig. 2 this decrement

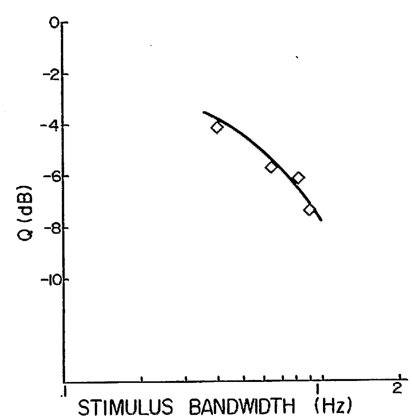

Fig. 5. The quality (Q) of smooth pursuit tracking decreases as the stimulus bandwidth increases.

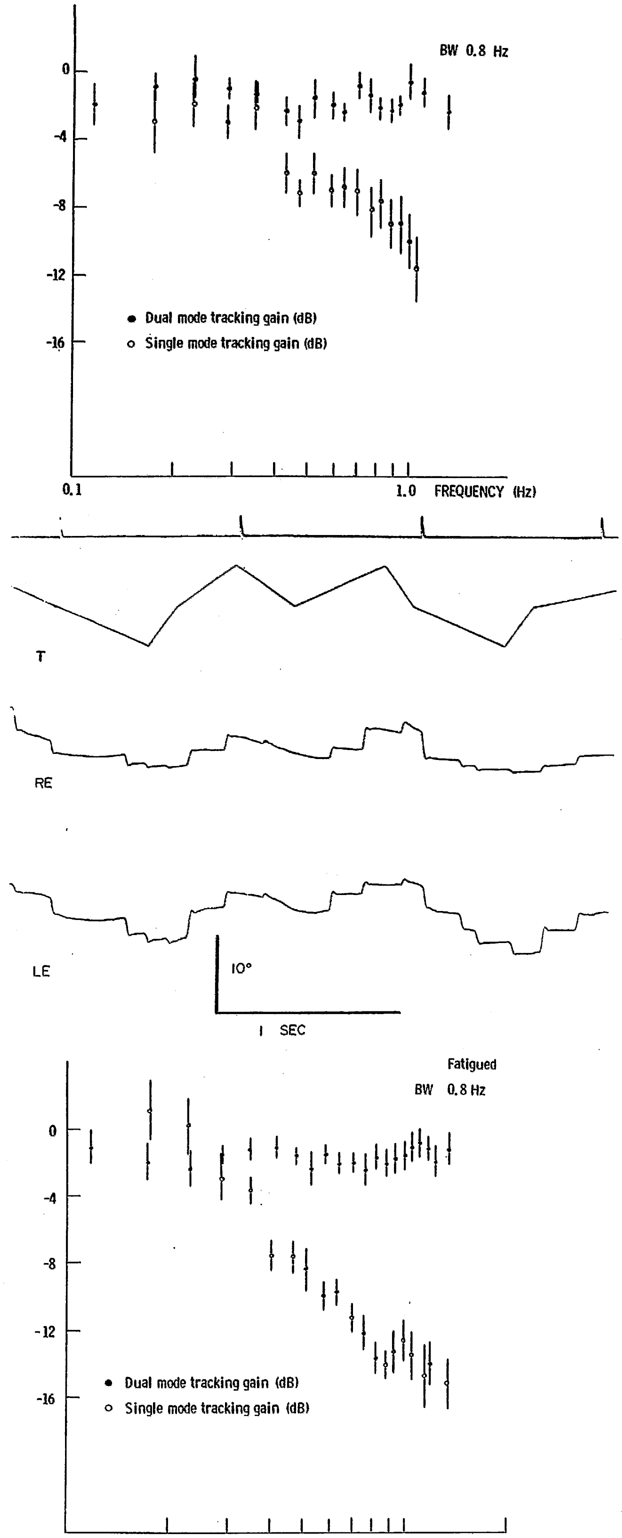

Fig. 6. Dual mode and single mode transfer functions for a subject in normal conditions (top). The subject then went 30 hr without sleep. His tracking (middle) was almost entirely saccadic. This produced a very large difference between the dual mode and single mode transfer functions (bottom) and a large value of Q. Stimulus bandwidth was 0.8 Hz for both conditions. Bars are 95% confidence intervals. Only data from the left eye were used to derive the transfer functions. The position traces are not identical because of a soft saturation of the right eye instrumentation channel on extreme left gaze. The subject was already tired when we began the fatigued trial, so we ran quickly. We only used the left eye to derive our transfer functions, so we only took care in adjusting the photocells of the left eye. We show both eyes here to demonstrate what is meant by a soft saturation of the recording system.

in performance is manifested by more saccades for the larger bandwidths. The quality factor, Q, decreases with increasing stimulus bandwidth as shown in Fig. 5. The 0.8 Hz bandwidth was the best for our purposes. It induced few saccades yet still had enough power around 1 Hz to allow a confident estimate of gain.

This Q factor is indeed just a way of quantifying the quality of the smooth pursuit tracking. The same conclusions could be derived from a careful analysis of the time domain records. The magnitude of Q is proportional to the number and size of the saccades in the record. For example, a fatigued subject will not have good smooth pursuit tracking and will follow a target using saccades. The data of Fig. 6 compare one subject when he is fresh and the same subject after going without sleep for 30 hr. The fatigued tracking was almost entirely saccadic and this shows up as a large difference between the single mode and dual mode transfer functions. The Q factor for the unfatigued situation was -5.4 dB, whereas the Q factor for the fatigued run was -11 dB.

The coherence function has a value between 0 and 1. It assumes its maximum value for noiseless, linear systems. For the unfatigued data of Fig. 6 the coherence function for the single mode tracking increased from 0.76 at low frequencies to 0.8 at 1 Hz. For the fatigued data of Fig. 6 the coherence function for the single mode tracking increased from 0.6 at low frequencies to 0.76 at 1 Hz (Fig. 7). The two coherence functions differed primarily in the low frequency region below 0.6 Hz.

The Q factor and the coherence function both differentiated between the normal and the fatigued person. However, they did so by looking at different regions of the frequency spectrum. Thus, they were complementary measures in the analysis of the effects of fatigue.

DISCUSSION

The dual mode tracking transfer functions derived from this study are similar to the results of previous investigators. The magnitude portion of the Bode diagram A of Fig. 3 can be approximated with a horizontal line between 0 and 1.2 Hz, and a line with a slope of -17 db/decade for higher frequencies. These approximations are rough but they provide a fairly simple transfer function.

$$G(s) = \frac{0.6}{s + 7.5}.$$

However, slight differences do exist, for example in the location of the peak in the dual mode tracking transfer function. The data from this study show a pronounced peak at 1.0 Hz, while the data of (Stark *et al.*, 1962) and (Dallos and Jones, 1963) have their peaks at 1.5 and 1.3 Hz respectively. This peak can be attributed to the frequency of occurrence and magnitude of corrective saccades in the eye movement response (Yasui, 1974; Iandolo *et al.*, 1978). An increase in the occurrence of corrective saccades for a given time record increases the effective bandwidth of the oculomotor response–dual mode tracking transfer function. Theoretically, if there were no corrective saccades within a given time record, then the dual mode transfer function would show the dynamics of only the lower bandwidth smooth pursuit subsystem. Because the peak in the dual mode transfer function occurs at a lower frequency than the peak in the transfer functions generated by the previous investigators, this indicates that the random velocity target waveform used in this study elicits better pursuit tracking.

When humans track periodic targets, they quickly lock onto the target movement and are able to track it with no latency. It is as if they create an internal model of the target movement and then track the output of this model, rather than the actual visual target. This internal model has variously been called a long term learning process (Dallos and Jones, 1963), a percept tracker (Yasui and Young, 1975; Young, 1977; Steinbach, 1976), a predictor (Stark *et al.*, 1962), and an adaptive controller (McDonald and Bahill, 1980). When small errors in tracking accumulate they are used to modify or update the model. This internal model is a part of the overall tracking system, but it is an additional component that we tried to eliminate from our first studies.

Clinical studies of the smooth pursuit system are not as common as clinical studies of the saccadic or vestibulo-ocular systems because of the large intersubject variability and lack of a quantitative measure for the goodness of smooth pursuit tracking. There is also a lot of intersubject variation in the magnitude and frequency of EEG alpha rhythm. Under the influence of anesthesia this variability disappears. In order to reduce the intersubject variability of human smooth pursuit we constrained the brain by restricting the regions that could be used in target tracking. We did this by eliminating the successful use of the part of the brain that analyzes the target movement and predicts future target position: we used unpredictable target stimuli.

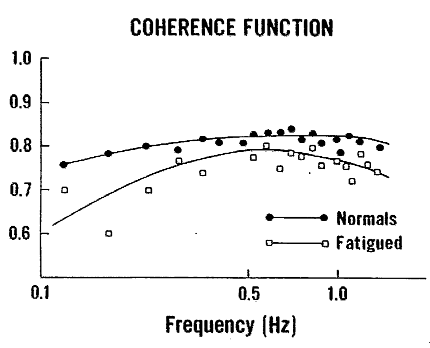

Fig. 7. The coherence functions for the single mode transfer functions of normals (top) and for the fatigued subject of Fig. 6. The coherence function takes on values between 0 and 1. It has a value of 1.0 for linear noise free systems. The reduction in coherence shown here is due to noise and to the presence and subsequent removal of saccades.

It may seem paradoxical that sinusoidal targets are easy to track, but there is great intersubject variability in tracking them. The use of an internal model, or predictive capability, may be the cause of this variability. The internal model is a high order process that is not stereotyped in all individuals. Its use would be affected by instructions to the subject and the subject's mental set. In contrast if the target movements are unpredictable, then the subject can not use the internal model and a possible source of variability is removed. We found that tracking unpredictable targets provided less intersubject variability.

The coherence function for the single mode transfer function (Fig. 7) reaches its peak around 0.5 Hz. It has smaller values for both higher and lower frequencies. The low frequency falloff is due to the removal of saccades, and to the presence of noise. Unless the number and size of rightward and leftward saccades are identical, the removal of saccades from the dual mode records will produce an offset, or a DC bias. This is a nonlinearity (power in the output that is not due to power in the input at that frequency). Nonlinearities reduce the value of the coherence function. Low frequencies correspond to slow target movements and therefore small eye movements. For smaller eye movements the signal will be smaller. The noise, both instrumental and biological (e.g. microsaccades), will remain the same, and therefore, the signal to noise ratio will become smaller. This also decreases the value of the coherence function at low frequencies. At high frequencies the coherence function is also smaller. At high frequencies there are more saccades in the record. Saccades are nonlinearities. Their presence reduces the value of the coherence function for the dual mode transfer function. But we remove them to construct the single mode tracking record. This removal is not perfect because there is probably a nonlinear interaction between the smooth pursuit and saccadic systems. This nonlinearity reduces the value of the coherence function. The coherence function of the fatigued subject had the same general shape as that of the normal subjects but it was reduced, particularly at low frequencies, due to the increased occurrence and subsequent removal of saccades in the records of the fatigued subject.

For our normal subjects the Q factor, was normally between -4 and -6 dB. As smooth pursuit tracking is replaced by saccadic tracking Q becomes smaller. It may also become smaller when an older population is studied (Sharpe and Sylvester, 1978). Patients showing little smooth pursuit tracking, such as those with progressive supranuclear palsy, are expected to show a wide separation between the dual mode and single mode tracking transfer functions, and small values of Q. Assuming that normal velocity small saccades are still present we would also expect a large peak in the dual mode tracking function plot between 1 and 2 Hz.

If a patient has an unidirectional pursuit abnormality the cumulative pursuit eye movement record will drift or have a bias shift in one direction or the other (Troost *et al.*, 1972). This will show up in the single mode transfer function as a high gain in the low frequency region and in the coherence function as low values for low frequencies.

We anticipate that the use of the Q factor, the coherence function, and a study of the shapes of the single mode and dual mode transfer functions will lead to better models of the smooth pursuit system and more precise analysis of pursuit abnormalities.

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