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# THE EFFECT OF WITHDRAWAL OF VISUAL PRESENTATION OF ERRORS UPON THE FREQUENCY SPECTRUM OF TREMOR IN A MANUAL TASK

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## SUMMARY

1. When a subject attempts to exert a steady pressure on a joystick he makes small unavoidable errors which, irrespective of their origin or frequency, may be called tremor.

2. Frequency analysis shows that low frequencies always contribute much more to the total error than high frequencies. If the subject is not allowed to check his performance visually, but has to rely on sensations of pressure in the finger tips, etc., the error power spectrum plotted on logarithmic co-ordinates approximates to a straight line falling at 6 db/octave from 0·4 to 9 c/s. In other words the amplitude of the tremor component at each frequency is inversely proportional to frequency.

3. When the subject is given a visual indication of his errors on an oscilloscope the shape of the tremor spectrum alters. The most striking change is the appearance of a tremor peak at about 9 c/s, but there is also a significant increase of error in the range 1–4 c/s. The extent of these changes varies from subject to subject.

4. If the 9 c/s peak represents oscillation of a muscle length-servo it would appear that greater use is made of this servo when positional information is available from the eyes than when proprioceptive impulses from the limbs have to be relied on.

## INTRODUCTION

The fine tremor of healthy subjects has been the subject of much experiment and speculation in the past but only recently have modern methods of frequency analysis been applied to the records (e.g. Halliday & Redfearn, 1956). In everyday usage the term 'tremor' refers to relatively rapid involuntary variations of position or pressure occurring several times a second; but when records of a voluntary contraction are analysed over a wide range of frequency down to one cycle in 2·5 sec (Sutton, 1957), or lower (Sutton & Sykes, 1967), there are no features that enable one to distinguish voluntary from involuntary activity in the spectrum. On a double logarithmic plot, the spectrum falls in a straight or slightly upward curved line from 0·4 c/s to the neighbourhood of 9 c/s, at about which point there is a peak of variable size (Sutton, 1957; this paper, Fig. 4).

Sutton's original records were obtained by inviting the subject to press upon a joystick with a force of 5 Lb. (2·3 kg) while he viewed a display of his errors on an oscilloscope. In the course of this work the singular observation was made that if the subject closed his eyes the peak in the tremor spectrum at 9 c/s immediately disappeared. This result was briefly described in a review article by Hammond, Merton & Sutton (1956).

## METHODS

The equipment was designed originally for the quantitative study of manual tracking. In point of fact the research had to be terminated before it had progressed beyond the preliminary stage of measuring the errors in the most elementary task of tracking a stationary

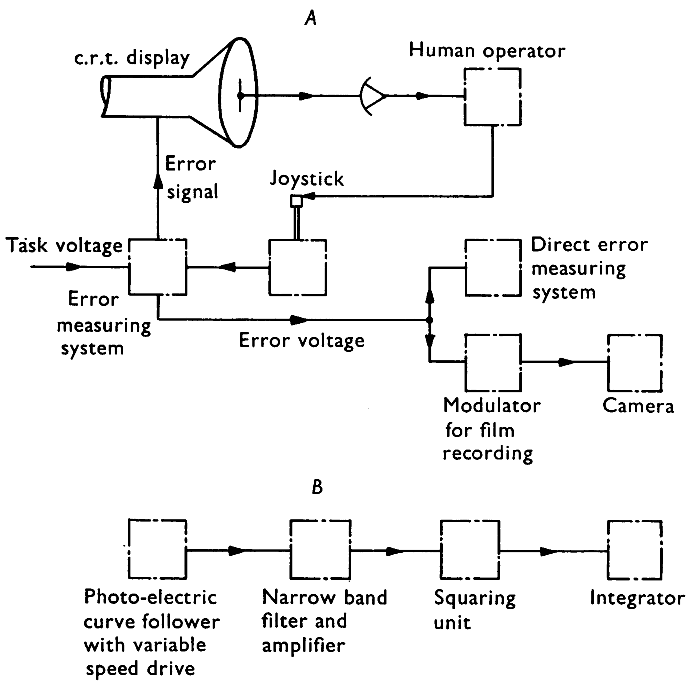


Fig. 1. *A*. Diagram of the experimental situation and of the recording system. *B*. The play-back system used for spectral analysis.

spot, i.e. maintaining a constant pressure on the control. If this had been foreseen the analysis could have been facilitated by recording only the action of a single muscle, such as the adductor pollicis, but, as it was, a short stiff vertical joystick was used which the subject held in much the same way as he would hold a pen. He was required to press upon it in a medial direction, with a force of 5 Lb. (2·3 kg); although many muscles are involved, this movement was chosen because it is one naturally used in manual tracking and all subjects are familiar with it. The compliance of the joystick was 0·010 in./Lb. (0·56 mm/kg).

Figure 1 shows the cathode ray tube (c.r.t.) display, the subject and the joystick control on a schematic diagram. The subject was seated opposite the c.r.t. with the joystick conveniently placed for his right hand. The forearm was supported in a splint which extended from just above the wrist to near the elbow, as shown in Fig. 2. The upper arm was vertical and just clear of the body. The top of the joystick was held between the thumb and fingers, as for writing, in a manner most comfortable for the subject. There was slight variation in the finger positions from subject to subject but inspection showed that the relation of the wrist to the joystick was similar for all subjects. The c.r.t. spot moved horizontally in the same sense as the sideways pressure applied to the joystick, the sensitivity being $\frac{5}{8}$ Lb./in. (0·11 kg/cm) c.r.t. deflexion. The subject's head was about 80 cm from the tube face.

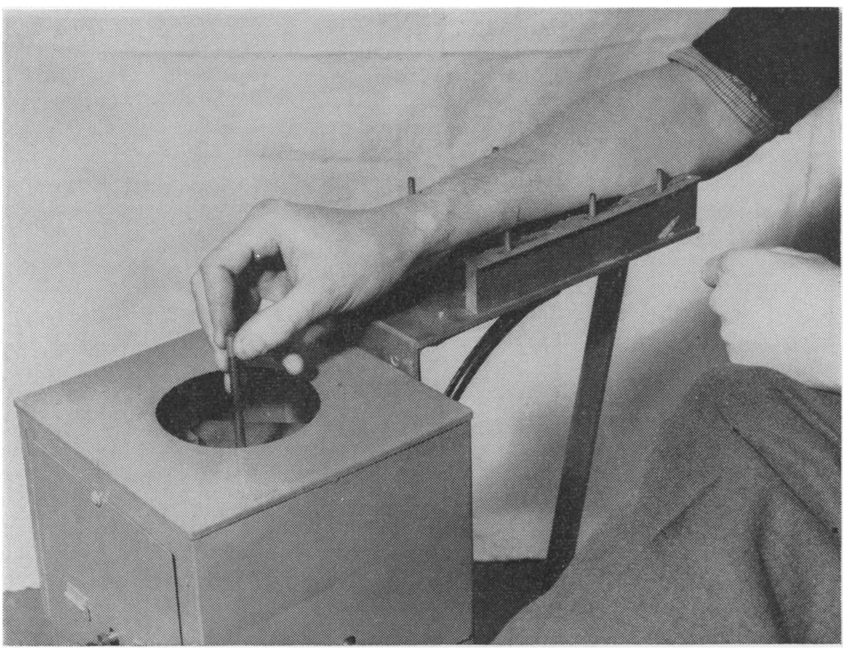

Fig. 2. The joystick operated by a subject.

The arrangements for recording the subject's error are also shown in Fig. 1. A varying voltage was derived, linearly proportional to the instantaneous error, i.e. to the distance of the c.r.t. spot from the aiming mark at the centre of the tube face. This voltage was used to modulate the length of a vertical trace on a small c.r.t., the image of which was focused on to 35 mm film which was driven through a special camera at a constant speed. After development, the film image obtained was a black 'profile' of the original error time function, an example of which is shown in Fig. 3. Full-scale signals on the film corresponded to either $\pm 0{\cdot}25$ cm or to $\pm 0{\cdot}51$ cm error on the subject's c.r.t., depending on the setting of a gain control, i.e. to force changes on the joystick of either $\pm \frac{1}{16}$ Lb. (0·028 kg) or $\pm \frac{1}{8}$ Lb.

(0·057 kg). The recording gain control did not affect the sensitivity of the subject's display c.r.t. There was a condenser coupling with a time constant of 8 sec in front of the recording system which prevented slow drifts from causing overload.

For analysis the film was 'played back' through the same camera and optical system, and the profile of the film image was followed by a photoelectric curve follower. The voltage derived from this system was at any instant proportional to the original error amplitude.

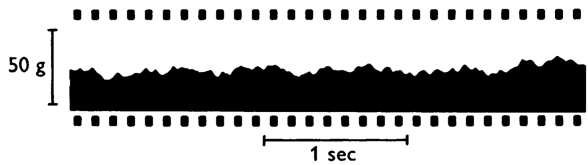


Fig. 3. A specimen of the type of tremor record obtained. The demanded force was 5 Lb. (2·3 kg).

This voltage was applied to a narrow band electronic filter which extracted the error at a particular frequency and, after squaring in a diode shaping unit, the signal was integrated by means of a low inertia integrating motor. The counted revolutions of this motor were thus proportional to the total squared error ('error power') in a narrow frequency band centred at the frequency of the filter. By playing back the film record at various speeds the effective frequency at which the error was measured could be altered and, after allowing for the effective bandwidth of the filter, a complete 'power' spectrum of the error was obtained. Further details are given in Sutton (1957).

Spectra are plotted as log. $(\text{error})^2$/unit bandwidth in arbitrary units against log. frequency. The arbitrary units were the same for all four subjects. The total $(\text{error})^2$ summed over all frequencies is, of course, the variance of the subject in performing the task. Thus the error power spectrum can be regarded as showing how the total variance is distributed as a function of frequency.

The subject's task was to align the c.r.t. spot with a fixed vertical mark at the centre of the tube-face. This required a medially applied force of 5 Lb. (2·3 kg) on the joystick, the c.r.t. spot having been offset to the right by a suitable bias voltage. The subject was instructed to maintain the spot on the central mark to the best of his ability and a recording was made lasting for 30 sec. He was then instructed to close his eyes and, after a short interval necessitated by this change, recording was again started for a further 30 sec. These two recordings constituted one experiment. The subjects were the same four healthy young men used by Sutton (1957). All of them had had considerable practice with the equipment. Sixteen experiments were carried out on each subject. The whole group of experiments was spread over 2 days, four experiments on each subject being carried out each morning and afternoon, with at least 30 min interval between experiments.

## RESULTS

Figure 4 shows the mean spectra for the sixteen 30 sec runs with the eyes open and the sixteen 30 sec runs with the eyes shut for subject M.D. Each record was analysed at forty-eight selected frequencies from 0·4 to 12·5 c/s but some of the experimental points have been omitted for the sake of clarity, mainly in the 6–10 c/s region. The bars at certain frequencies are of length twice the standard error of the mean.

The most striking difference between the two spectra is the absence of the 9 c/s peak with the eyes shut; but the eyes shut spectrum also tends to be straighter throughout its whole length and thus lies above the eyes open

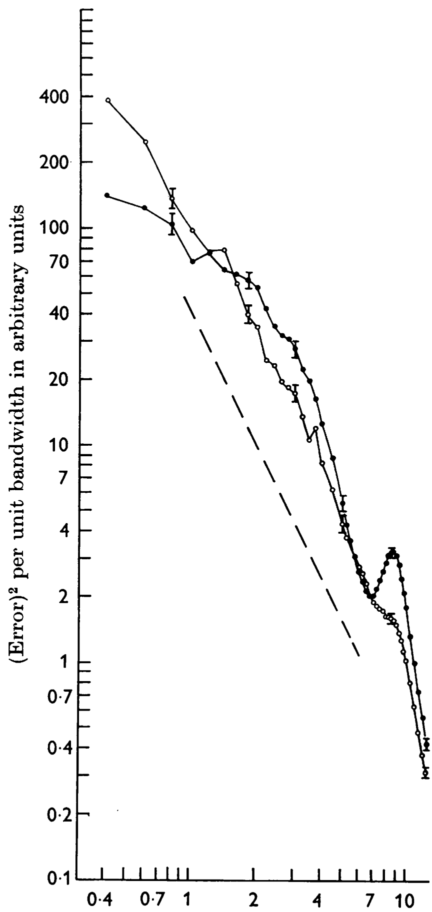


Fig. 4. Mean error spectra with the eyes open (●) and shut (○) for subject M.D. The error bars represent twice the standard error of the mean. The interrupted line has a slope of 6 db/octave.

spectrum at frequencies less than about 1 c/s and below it between 1 and 4 c/s. These differences, like the difference between the two in the region of the 9 c/s peak, are highly significant statistically ($P < 10^{-5}$ at the peak, $P < 10^{-3}$ from 0·4 to 0·6 c/s and from 2·0 to 3·3 c/s). The eyes shut spectrum has a slope of $-6$ db/octave corresponding to the relationship, error amplitude inversely proportional to frequency.

The degree of significance of the difference between the spectra has been calculated at each frequency although, in most cases, the readings at adjacent frequencies are not independent. Owing to the finite bandwidth of the filters used in analysing the records, energy at a given frequency may contribute to the readings at several adjacent frequencies, thus making the readings more or less dependent. However, for practical purposes it may be assumed that alternate readings are independent at frequencies above 1·2 c/s and that adjacent readings are independent at 1·2 c/s and below. It was found that there was good correlation between the readings obtained for the eyes open and eyes closed records in the same experiment, and so account was taken of this in calculating the probabilities.

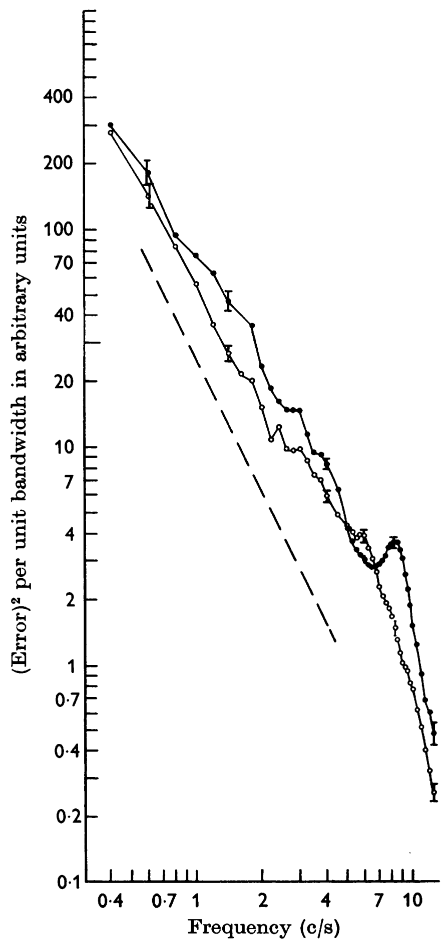


Fig. 5. Eyes open (●) and eyes shut (○) spectra for subject J.B. (see also legend to Fig. 4).

The other three subjects show similar alterations in the shape of the error spectrum with the eyes shut, but the differences are less conspicuous than for subject M.D. The mean spectra for these subjects are shown in Figs. 5, 6 and 7. Only J.B. has a clear-cut peak which disappears with the eyes shut (the difference between the two spectra at the peak being highly significant with $P < 10^{-5}$). Both G.G.S. and K.S., however, have a distinct upward trend in their eyes-open spectra in the 7–9 c/s region, which flattens out with the eyes shut. For G.G.S. the separation is significant

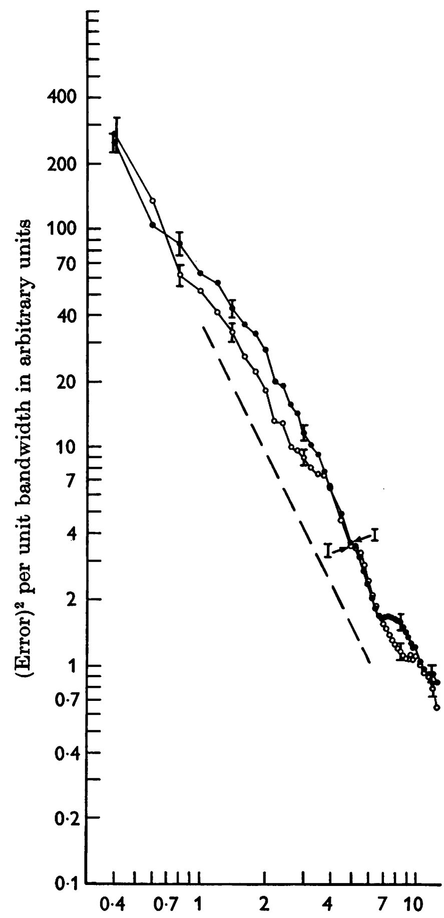


Fig. 6. Eyes open (●) and eyes shut (○) spectra for subject G.G.S. (see also legend to Fig. 4).

with $P \leqslant 10^{-2}$ over the frequency range 7·75–9·25 c/s, and $P < 10^{-3}$ at the best point. For K.S. the separation of the eyes-open and eyes-closed curves is probably significant ($P \leqslant 0{\cdot}05$) over the range 5·75–7·75 c/s with $P \sim 0{\cdot}01$ over a small range (6–7 c/s). The most significant separation is at about 7 c/s, a clearly lower frequency than for the other three subjects.

As with the first subject the eyes shut spectra in Figs. 5, 6 and 7 are straighter over the whole range than the eyes open spectra and have a slope of roughly 6 db/octave. The straightening out is conspicuous for J.B. and G.G.S. and is statistically significant. Thus for J.B. the two spectra

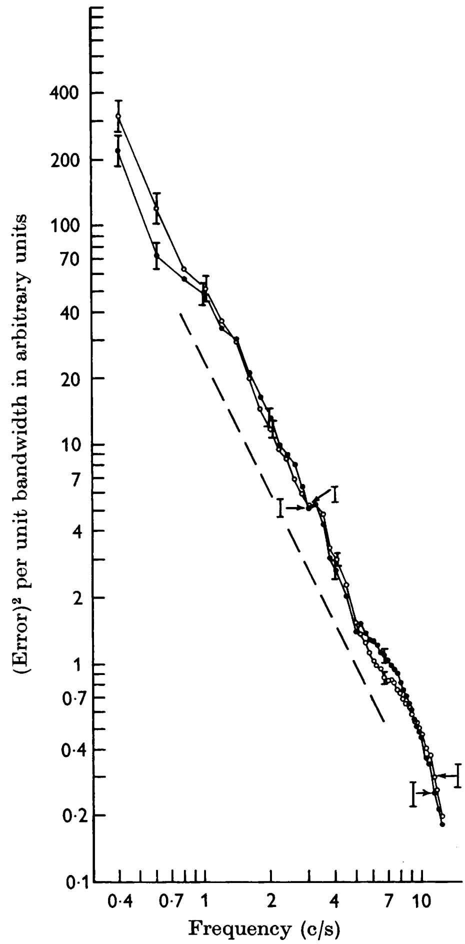


Fig. 7. Eyes open (●) and eyes shut (○) spectra for subject K.S. (see also legend to Fig. 4).

differ at the 0·1 % level of significance from 1·3 to 3·0 c/s, and for G.G.S. (at the same level) from 2·2 to 3·0 c/s. For K.S. the two spectra do not differ significantly in this middle range, but they are both straight anyway and have a slope remarkably close to 6 db/octave.

Above the region of the 9 c/s peak all the curves fall more rapidly. Measurement shows that, where there is a clear slope, it is close to 18 db/octave, both with the eyes open and with them shut.

From inspection of Figs. 4–7 it is not evident whether the total error over the whole range analysed is on the whole greater or less with the eyes shut, but since the subjects were observed to drift slowly off the mark when their eyes were shut (to the extent of some 5–10% of the force exerted) it is

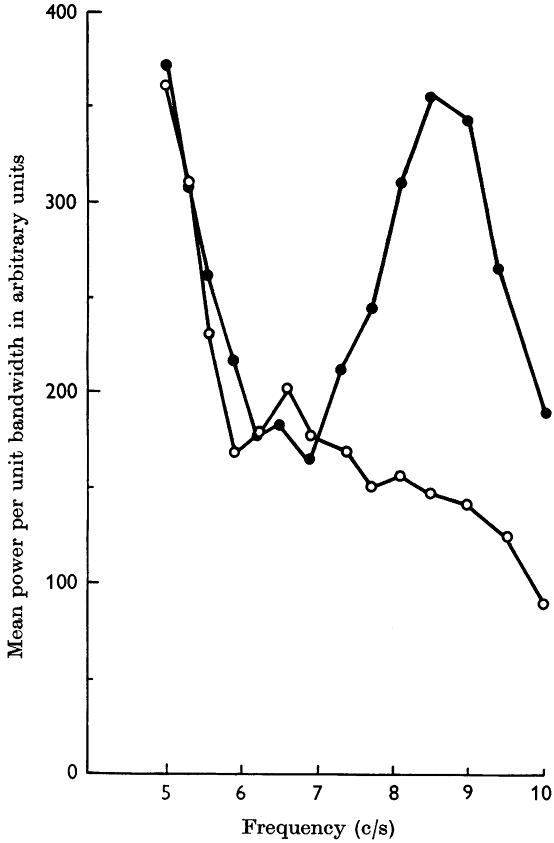


Fig. 8. Error spectra for subject M. D. with the display cathode ray tube in action (●) and with the spot extinguished (○). (Only a limited region of the spectrum is plotted, on linear scales.)

clear that at any rate at lower frequencies than those dealt with here the errors must have been substantially greater when the eyes were shut. This was confirmed by playing back the film records into the equipment for frequency analysis, but without a filter, to obtain a measure of the total square error over all frequencies down to 0·02 c/s (the lowest frequency nominally passed by the condenser coupling). In each case the total squared error was greater with the eyes closed than with the eyes open.

*Effect of extinguishing the display cathode ray tube.* The 9 c/s tremor peak also disappears if the spot on the display c.r.t. is extinguished, instead of the subject closing his eyes. Figure 8 gives mean curves for two experiments on subject M.D. Two experiments on subject J.B. (who also had a pronounced 9 c/s peak) gave similar results. This is taken to show that closing the eyes acts as it does only because it deprives the subject of visual information about his errors.

*Experiments with the order reversed.* In the main series of experiments the eyes open run always preceded the eyes closed run. As a precaution experiments were done with the order reversed. After enough time to align the c.r.t. spot the subject closed his eyes and a 30 sec run was made. This was followed by a 30 sec run with the eyes open. In these experiments the error voltage was applied directly to a fixed filter centred at 8·5 c/s with a bandwidth of $\pm 1$ c/s and the $(\text{error})^2$ at 8·5 c/s measured at once. The errors were not recorded for spectral analysis.

All subjects showed a considerably increased score in the second half minute (i.e. with the eyes open). Hence there is no reason to suspect that the order in which the recordings were made has anything to do with the reduction of the 9 c/s peak.

*Mechanical resonance in joystick and hand.* The possibility was considered that the tremor peak at 9 c/s might have nothing to do with the stretch reflex, but might be due to some natural resonance of the mechanical system consisting of the hand and joystick. (The joystick itself had a natural resonance at about 75 c/s when given a small displacement and allowed to oscillate freely.) Accordingly an experiment was carried out to determine whether the inertia of the hand and joystick affected the tremor frequency. A mass was attached to the joystick so as to double approximately the effective moment of inertia of the hand about the wrist joint, and a pen recording made of the subject's error while maintaining a force of 5 Lb. (2·3 kg) on the joystick in the usual manner. This was compared with a recording made immediately afterwards, when the additional mass had been removed; but direct measurement of the records showed that there was no noticeable change in the frequency components. This is in accord with the findings of a similar experiment carried out by Halliday & Redfearn (1956).

It appears safe therefore to discount the possibility that the tremor peak was brought about by what might be called a 'local' resonance produced, for example, by a combination of mass and compliance in the hand and wrist.

## DISCUSSION

The results have shown fairly definite evidence for the reduction of tremor activity around 8 c/s when a visual stimulus is removed. In two of the subjects the effect is very marked, in one it is not so definite and in the remaining one it is only just observable. It is important also to recognize that in addition to the reduction so far considered there is also a marked reduction of activity in the region 1–4 c/s in three of the four subjects. It is not impossible that the activity in this region is produced by 'break through' from another muscle group (e.g. biceps) with a tremor frequency lower than that pertaining to the wrist muscles and giving a similar reduction with the eyes closed. The manner of holding the joystick and supporting the forearm could allow the arm muscles to influence the results. Consequently a composite picture of two muscle groups of different sizes and therefore possibly different tremor frequencies might have been obtained. It is obviously necessary to investigate more fully tremor frequencies in muscles controlling different members of the body.

Another reason for the reduction in activity at frequencies below the tremor peak when the eyes are closed might be that the nature of the corrective movements made in this condition differs from that of the corrective movements made with the eyes open. It is fairly certain that this will be so, since with the eyes closed the only information the subject can receive about deviation from his set task is by way of proprioceptors. If a larger threshold exists in this channel than in the visual one it is possible that the subject will make corrections less frequently and hence the spectrum of his response to errors will be modified. The idea that corrective movements are not smooth and continuous but take place in a discrete and jerky manner is not new. For example, Hick (1948) discusses the matter and suggests that corrective movements in a tracking task are made every 0·5 sec. It is interesting therefore to examine briefly the form of the power spectrum which would be obtained from a response of this kind. It can be shown (Rice, 1944, p. 310) that the power spectrum of a flat top and bottom wave, whose amplitude is either $+a$ or $-a$ and in which the duration of either of these amplitudes is distributed independently and exponentially, falls off with frequency exactly in the same way as would the output from an exponential lag with an applied signal of constant amplitude, i.e. at 6 db/octave above the 'corner' frequency (the frequency at which the signal is 3 db down on the low frequency level). In one form of the theory the corner frequency $f_c$ is given by the expression $f_c = \mu/\pi$, where $\mu$ is the most probable number of changes of sign of the amplitude per second. With $\mu = 2$ from Hick's figure of 0·5/sec for the rate of corrective movements, $f_c = 0{\cdot}64$ c/s, which is not unreasonable for some of the eyes-open spectra. A lower value of $\mu$ giving a lower corner frequency would clearly accord better with the eyes-shut spectra and with the spectrum for K.S. with his eyes open. Examination of the actual film records, however, shows little evidence for clearly marked 'step' corrections. There are apparently large low frequency corrections and these must, likewise, produce a large amount of power at low frequencies falling off at higher frequencies.

An alternative hypothesis, which is applicable to the eyes-closed spectra and which gives the same result, supposes that when deprived of visual information about the position of the c.r.t. spot the subject has to rely on sensations from skin and joint receptors, which are known to be sensitive mainly to rate of change of stimulus. The attempt to hold a position constant using effectively velocity information leads to errors, the size of which is inversely proportional to frequency; and hence to a slope of $-6$ db/octave in the power spectrum. This hypothesis does not apply to the subject's performance with his eyes open, when action is taken on the positional errors themselves. In this mode of operating the power spectrum would again become level below a certain frequency. Such a flattening out can be seen in the spectra of M.D. and to a less extent in those of J.B. and G.G.S.

It is clear from the general slope of all the curves that there are three distinct regions: one below about 6 c/s whose average slope follows quite well the 6 db/octave line, one above about 10 c/s which follows the 18 db/octave line and the third region which is the tremor peak itself.

One possible reason for the appearance of the tremor peak is that it is produced by activity in the muscle servo loop based on the spinal stretch reflex (Hammond *et al.* 1956; Halliday & Redfearn, 1958). Such a servo need not necessarily be unstable to produce such an effect. For example, a servo mechanism having characteristics similar to a damped tuned circuit could accord more gain to inputs at or near its natural resonant frequency. Such a servo supplied with an input which might be described as 'noisy' arriving, say, down the $\gamma$ pathway, would accentuate those parts near its natural resonance and produce the effect which is being considered. In order to explain the decrease in activity with the visual stimulus removed it is necessary to postulate a change in one or more of the parameters of such a servo when attention has been reduced. If the sensitivity of the system depends on attention then it is not difficult to explain a change taking place, although the precise nature and position in the servo loop of such a variation is difficult to postulate. The only direct evidence for such a change in gain was an effect observed in electromyographic activity in biceps by P. H. Hammond and one of the authors (G.G.S.) in connexion with small force applications to the forearm (see Hammond *et al.* 1956). In that experiment a subject was instructed to reposition his arm or take no action when a small increment was added to a force already being maintained. The experiment was carried out with eyes open and eyes closed. The biceps electromyogram which could almost certainly be ascribed to reflex activity after the force application was noticeably less with the eyes closed than with the eyes open, particularly so when the subject was instructed to take no action. It is noticeable from the spectra for subject M.D. (shown in Fig. 4) and subject J.B. that the curves become smoother as the tremor peak is approached until, at frequencies above the peak, the experimental points lie remarkably on a straight line. This fall-off on a straight line after the peak is precisely the effect which is produced by the characteristics of a resonant circuit when plotted on logarithmic axes. The fact that the fall-off is in most cases remarkably close to 18 db/octave is explained by the fact that the resonance would produce a fall-off finally at 12 db/octave (effectively two exponential lags) to which must be added the fall-off of 6 db/octave which precedes the peak.

Calculation shows that there is good correlation between the eyes open and eyes closed readings in the same experiment of all subjects at the higher frequencies. It is tempting to suppose that the more erratic parts of the spectra at the lower frequency end are the products of voluntary activity on the part of the subject and the more consistent smooth parts are due to some mechanism outside voluntary control and therefore more reproducible.

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