Intermittency in Human Manual Tracking Tasks

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ABSTRACT. We confirm Craik's (1947) observation that the human manually tracking a visual target behaves like an intermittent servo-controller. Such tracking responses are indicative of "sampled" negative-feedback control but could be the result of other, continuous, mechanisms. Tracking performance therefore was recorded in a task in which visual feedback of the position of the hand-held joystick could be eliminated. Depriving the subjects of visual feedback led to smoother tracking and greatly reduced the signal power of their responses between 0.5–1.8 Hz. Their responses remained intermittent when they used feedback of their own position but not of the target to track a remembered (virtual) target. Hence, intermittency in tracking behavior is not exclusively a signature of visual feedback control but also may be a sign of feedback to memorized waveforms.

Craik's (1947) suggestion that the intermittency is due to a refractory period following each movement was also tested. The errors measured at the start of each intermittent response, during tracking of slow waveforms, showed evidence of a small error deadzone (measuring 0.7 cm on the VDU screen or 0.8° at the eye). At higher target speeds, however, the mean size of starting errors increased, and the upper boundary of the distribution of starting errors was close to that expected of a refractory delay of approximately 170 ms between responses.

We consider a model of the control system that can fit these results by incorporating an error deadzone within a feedback control loop. We therefore propose that the initiation of intermittent tracking responses may be limited by a positional error deadzone and that evidence for a refractory period between successive corrective movements can be satisfied without evoking an explicit timing or sampling mechanism.

Key words: feedback control, sampling, visuomotor tracking

There is a clear difference between tracking of smoothly moving visual targets with the human eye and with the arm. The eyes tend to pursue the target continuously, and only to break down into discontinuous saccades when the target begins to move faster than the smooth pursuit system can manage. In contrast, the limb tends to move discontinuously, and only achieves smooth pursuit of predictable targets as their speed increases. Some of this difference almost certainly is due to the relative simplicity of the control of a spherical eyeball rotating in a solid supporting cup compared with the complexity of a multijointed limb moving in a gravitational field. Because of the complexity of the limb mechanics, one might expect less accurate and hence less smooth motion than is possible with the eye. There is good reason to think that the intermittent behavior of the limb is not due just to poor motor performance, however, but that it is a strategy that is deliberately adopted to optimize limb control in difficult circumstances. In 1947, Kenneth Craik suggested that the human performs as a "sampled servo-controller" in manual tracking tasks, and discussed the advantages of such regularly sampled control systems. He suggested that the intermittent process was therefore a fundamental component of the limb control system. If additional tracking cues were provided, intermittency then was observed to diminish. So, for example, predictable sine waves can be followed without intermittency (Craik, 1947; Poulton, 1974; Weir, Miall, & Stein, 1989). Note that in this article we use the term *intermittency* as a description of the subjects' responses rather than as a description of the causal mechanism.

There seems little doubt that Craik's (1947) idea that human tracking performance is analogous to that of an intermittent servomechanism is generally correct, but as far as we know there have been no clear tests of the basic assumptions behind his work. One implication of his theory of a sampled servo-controller is that the intermittency is dependent upon the use of feedback information. In other words, if the feedback loop were opened, then the servo-controller no longer ought to be able to generate error signals to evoke

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new responses. We therefore tested this hypothesis in human subjects tracking a visual target with a hand-held joystick under two experimental conditions. First, we deprived them of visual feedback information of the position of the joystick; and second, we removed the subjects' view of the movements of the visual target so that they had to track from memory.

A second question that we raise here concerns the nature of the sampling mechanism. Three possibilities have been suggested. The first, that some form of internal clock simply times out the series of movements (Bekey, 1962; Lemay & Westcott, 1962), is easily disproved. The rate of movements observed is not constant from moment to moment, but depends on, among other things, the rate of target motion, the size of the movements made, and on the delay in feedback of results (Miall, Weir, & Stein, 1985; Pew, Duffendack, & Fensch, 1967; Smith & Sussman, 1970). A second proposed mechanism is that an error deadzone inhibits small movements (Navas & Stark, 1968; Stark, 1968). In other words, there may be a threshold above which the positional error must rise before a corrective movement is started. A third proposal is that a refractory period interposes between each corrective response. In other words, there may be a fixed minimum interval between two movements (Neilson, Neilson, & O'Dwyer, 1988; Smith, 1967; Vince, 1947). Craik (1947) argued that an error deadzone was unlikely, on the grounds that human visual acuity is too high to be responsible, and that movement rate does not change with target frequency. He therefore favored the refractory period mechanism. In contrast, we have suggested (Miall, Weir, & Stein, 1986) that an error deadzone best fits the tracking behavior of monkeys. Therefore, we have reexamined these last two possibilities in human subjects by measuring the errors at the start of their corrective responses, and the time interval between them.

These experiments indicate that Craik's (1947) view of the human as a sampled servo-controller probably should be modified in three ways. First, the controller generating intermittent corrective limb movements does not likely operate only on the basis of current signals provided by the visual system but also can make use of memorized target waveforms. Hence, the presence of intermittency is a signature of error control but not exclusively of on-line visually defined error control. Second, there seems to be evidence for a positional error deadzone underlying intermittency. Third, the rate of movements, although heavily influenced by delays in the visual feedback pathway, may also reflect delays within nonvisual feedback paths. We suggest that evidence pointing to a combination of both an error deadzone and a refractory period underlying intermittency may instead be modeled by a positional error deadzone combined with a delay in the loop providing visual feedback.

Method

The experiments reported here form part of two series of tests on normal human subjects.

Series 1

This series comprised 8 subjects: 6 males, 2 females; age range 22–34. The subjects were, with one exception, new to the task, but each was allowed several minutes practice before any data were collected. No gross differences in their responses were seen. Almost all the data presented were taken from a single session of 12 consecutive trials of different tracking conditions. The order of trial presentation was maintained across subjects. Each trial lasted 1–2 min, depending on the waveform used, and trials were separated by a pause of 10–30 s. The data in Experiment 2 (Part b) was collected in a second session of 5 trials under the same experimental conditions; the data in Experiment 3 (Part b) was collected as part of Series 2 (see below).

Each subject sat approximately 50 cm in front of a 30-cm monochrome computer monitor (with 640- × 399-pixel resolution) on which a target was displayed as a small rectangle (2 × 4 mm). He or she was required to use a hand-held joystick to track the horizontally moving target as accurately as possible. The position of the target was controlled by the experimental computer and followed a sinusoid of selected frequency or a pseudorandom path. The pseudorandom waveform was generated by the sum of four nonharmonic sinusoids (0.073, 0.117, 0.205, and 0.278 Hz, all of equal amplitude; see Figure 1). It had a repeat period of 25 s and a peak velocity of $14°s^{-1}$. The target could move 20 cm across the screen, that is, about 23° at the eye. The joystick was a light-weight, low-friction, unsprung model (Radio Spares 162–984 with the self-centering spring removed). It was 8 cm in length and needed to be moved through ±19° to follow the target, or 4.5 cm at its tip. The horizontal position of the joystick was digitally sampled at 60 Hz with 12-bit resolution and was displayed on the monitor as a small spot (the *monitor spot*, of 1 × 2 mm). Vertical movement of the joystick was disregarded and did not affect the monitor spot. There were no dynamics between the joystick and monitor spot display. Arm movements were unrestricted, although for comfort some subjects rested their elbow on a support. The positions of the target and joystick were sampled at 60 Hz and saved onto disk after each trial. Each trial ran for either 50 or 100 s, depending on the target waveform used, with a pause between trials of 10–30 s.

Series 2

Some minor details of the experimental conditions differed from the first series; full details of the protocol used have been given in Weir et al. (1989). The principal changes were that 4 male subjects were used (age range 24–45)—all had only limited experience of the tasks but were given several minutes practice before data collection; the joystick was 17 cm in length, rather than 8 cm, and was moved through ±25°; the screen was larger (56 cm) but farther away, subtending the same angle at the eye; sampling of the waveforms and screen refresh rates were 50 Hz; and finally, the target was a vertically aligned pair of dots, rather than a small rectangle. Only data presented in Experiment 3 (Part 2) came from this series.

Tracking Paradigm

Two basic tracking paradigms were used, *pursuit tracking,* in which the subject attempted to match the position of the moving target with the monitor spot, and *compensatory tracking,* in which the monitor spot was offset from the central, stationary, target by the test waveform. The subject's task then was to compensate for this displacement and return the monitor spot to the screen center.

Experiment 1: Tracking without Visual Feedback

a. Pseudorandom Target

Eight subjects were instructed to follow a pseudorandom waveform for 50 s with pursuit tracking. They were warned that the monitor spot providing visual feedback of the joystick position would be extinguished, and asked to continue tracking "as if the monitor spot were still visible." The waveform had a repeat period of 25 s, and the monitor spot was extinguished for the third and fifth 8.3-s epoch (500 samples) within the 50-s trial. The second and sixth 8.3-s epochs were selected as controls, providing two matched sets of 2- × 8.3-s records, two with feedback and two without.

b. Sinusoidal Target

Four of the 8 subjects were instructed to pursue sinusoidal target frequencies of 0.04, 0.06, 0.08, 0.167, and 0.41 Hz, each presented for 50 s. The monitor spot was extinguished for two 8.3-s epochs, as previously, timed so that it disappeared or reappeared as the target passed through the center of the screen. Two matched segments of the waveform were taken at each frequency as controls.

c. Analysis of Signal Power

The record of joystick position was digitally differentiated (to emphasize the high-frequency response components at the expense of the lower-frequency target components) and the power spectrum of each 8.3-s record of joystick velocity calculated (Fast Fourier Transform: 500 samples per record, after removal of the record mean and padding with zeros to 512). The difference between the power spectrum of each test and control epoch of tracking was found (by subtraction of the with-feedback spectrum from the without-feedback spectrum), and the two difference spectra per subject were added together. The resulting four or eight spectra then were averaged.

Experiment 2: Tracking an Imaginary Target

a. Target Waveforms

The same 8 subjects tracked a 0.167 Hz sinusoidal target, again for 50 s, with pursuit display. The target waveform was displayed for the first 25 s and then extinguished, leaving only the monitor spot on the screen. The subjects were warned of this, and instructed to continue tracking "as if the target were still visible." In addition, 4 of these subjects tracked sinusoids at frequencies of 0.04–0.41 Hz (see above) under otherwise identical conditions.

b. Analysis of Signal Power

As previously, each test epoch (without a visible target) was compared in the frequency domain with a control epoch (when the target was visible). In this case, the difference spectra of the 25-s epochs before and after the disappearance of the target were calculated (n = 8 subjects; 1,500 samples, mean removed and padded with zeros to 2048).

Experiment 3: Measurement of Start and End Error Distributions

a. Pseudorandom Waveforms

The 8 subjects were instructed to pursue a pseudorandom waveform for 50 s. The waveform was identical to that used previously in Experiment 1. The subjects then followed the same pseudorandom target but under compensatory tracking conditions (in which only their positional error was displayed on the screen). Finally, the subjects followed a 0.08 Hz sinusoid, again by means of compensatory tracking. In all cases, the subjects were required to follow the target as accurately as possible and both monitor spot and target were visible throughout. Data from two trials was corrupted before analysis, so results are presented from the remaining 6 subjects only.

b. Sinusoids

In a separate experimental session (Series 2) 4 subjects were asked to follow sinusoidal targets of 0.05, 0.1, and 0.2 Hz, by means of compensatory tracking.

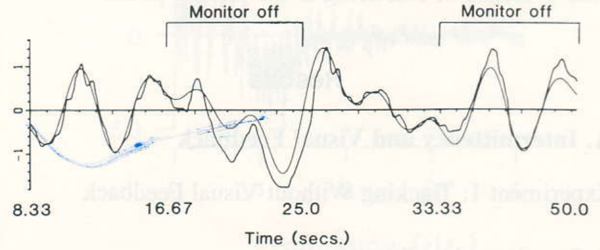

FIGURE 1. Typical tracking with and without visual feedback. The smooth line shows the pseudorandom target waveform, and the thick line the response of the subject. Notice the clear signs of intermittent positional responses, which are greatly reduced in the two periods when the monitor spot providing on-screen feedback of the joystick position was switched off (horizontal brackets).

c. Measurement of Errors

The start and end of each positional correction was computed automatically. The procedure was as follows: The digitized record of joystick position was duplicated, and one copy digitally filtered to 4 Hz with a fourth-order, zero-phase Butterworth low-pass filter. This signal then was differentiated digitally, and a velocity window of $\pm 2°s^{-1}$ applied (measured as movement of the monitor spot across the screen). The times at which the velocity signal left the window (i.e., velocity exceeded $2°s^{-1}$) were taken as the start of each movement; the times at which the signal reentered the velocity window (velocity below $2°s^{-1}$) were taken as the end of each movement. The chosen times then were replotted on the original, unfiltered, position records, allowing the operator to exclude by eye any inappropriate points. Lastly, the magnitude of positional error between the target and the unfiltered joystick signal was measured at each of the selected start and end times, and plotted as a histogram. Histograms from all 4–8 subjects were averaged, and the range between ± 1 *SE* of the mean was plotted.

A small number of false positives were detected, usually near the turning points of the target waveform, when the subject's average velocity was only just above the threshold of $2°s^{-1}$. If the position record looked smooth, then these false positives were rejected by the operator. The computer algorithm worked well for the great majority of the data, however, and the number of points rejected from each trial in this way was small, often zero, averaging about 2% of the total number of movements. No points were added to those objectively found. Note that the algorithm would break up falsely a completely smooth response into a small number of movements, one for each time the response slowed down and reversed direction, and in a 0.2-Hz sinusoid, about 4% of the total record would be detected as nonmovement, clustered at the turning points of the target motion. About 8% of the subjects' compensatory responses to such a target typically were detected by the algorithm as nonmovement, distributed throughout the target cycle, with little evidence of clustering at the turning points.

Results

A. Intermittency and Visual Feedback

Experiment 1: Tracking Without Visual Feedback

a. Pseudorandom Target

A typical example of pursuit tracking of the pseudorandom target is shown in Figure 1. The power spectra calculated from this record are shown in Figure 2. Figure 2A shows the power spectrum of the control tracking, with full visual feedback of the monitor spot. It contains a broad region of power between 0.8 and 1.8 Hz, which is attributable to the intermittent nature of the response (see also Miall et al., 1985). Figure 2B shows a clear reduction in the power across this region when the subject was tracking without visual feedback.

b. Sinusoidal Target

Figure 3 shows ± 1 *SE* of the mean of power spectra from 4 subjects tracking a low-frequency sinusoid. As with the pseudorandom target, a broad band of power is seen between about 0.5 and 1.5 Hz when the subjects were tracking with visual feedback (Figure 3A); Figure 3B shows a clear reduction in signal power within this frequency band.

c. Difference Spectra

Figure 4 shows the average difference spectra calculated by subtracting the power spectra of tracking responses with feedback from those without. Figure 4A is from pseudorandom tracking, Figures 4B-E are from four different frequencies of a sinusoidal target. The black areas in each graph are again the region within ± 1 *SE* of the mean of these averages. Regions of negative power indicate frequencies at which there was a reduction in signal power when the subjects were deprived of visual feedback. In every graph, a negative region lies between 0.5 and 1.5 Hz, the same frequency band at which the intermittent responses contribute power. Hence, in tracking without visual feedback, there was a significant reduction in the intermittent nature of tracking responses.

Experiment 2: Tracking an Imaginary Target

A typical response is shown in Figure 5. Although sinusoidal targets were pursued much more smoothly than were pseudorandom targets (compare the intermittency of Figure 1 with Figure 5), some intermittent responses can still be seen (as evidenced by the power band at about 1 Hz in

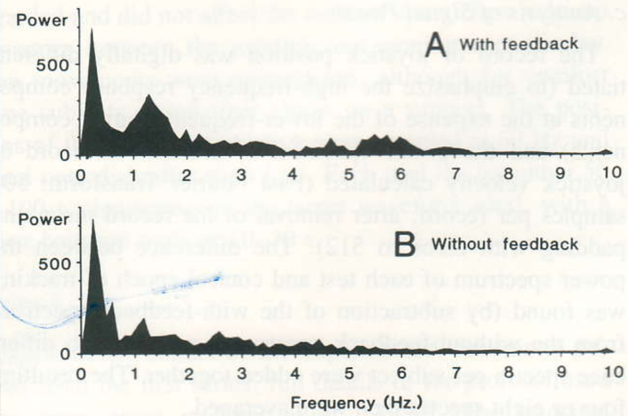

FIGURE 2. Velocity power spectra calculated for a single subject from the differentiated positional record of Figure 1. The upper spectrum **(A)** was calculated from the first 8.3 s of the velocity record, the lower one **(B)** from the first 8.3-s period without visual feedback. The spectral band below 0.4 Hz is due to the frequency components of the target, whereas the band between 0.8 and 1.8 Hz indicates components of the velocity signal due to the intermittent nature of the subject's responses.

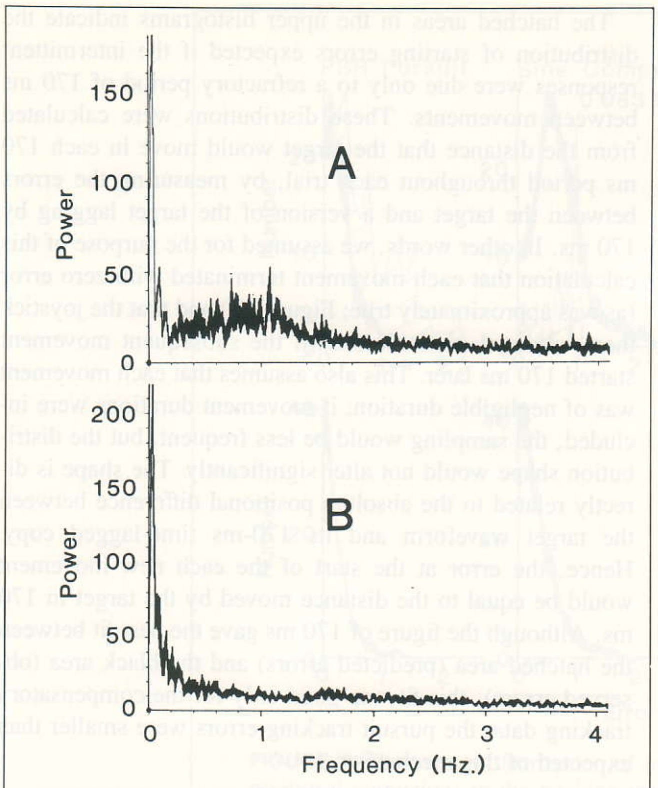

FIGURE 3. Average velocity power spectra from 4 subjects tracking a 0.04 Hz sinusoid with (**A**) and without visual feedback (**B**). The black area in each graph indicates ± 1 *SE* about the mean of eight spectra, two from each subject, calculated from 8.3-s epochs of the velocity response.

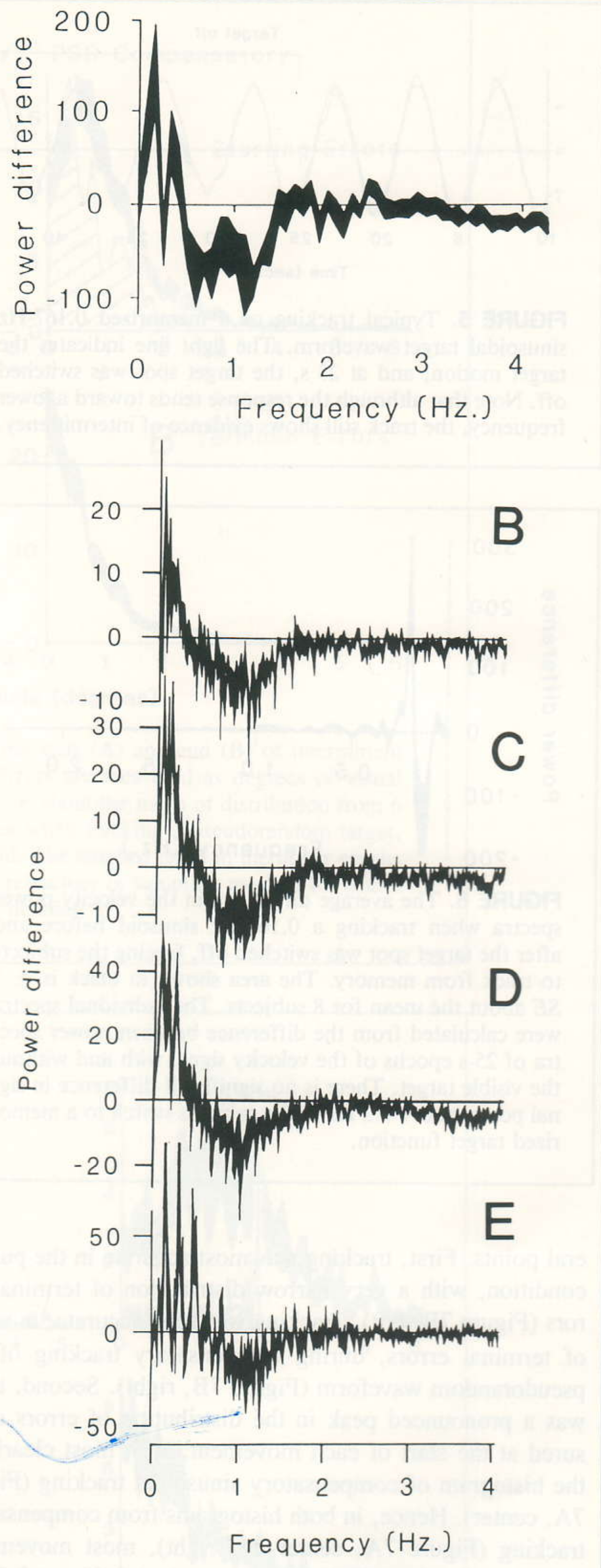

FIGURE 4. Average difference spectra, obtained by calculating the difference between power spectra such as those shown in Figure 2. (**A**) The area plotted is ± 1 *SE* about the mean of eight difference spectra, one per subject, tracking pseudorandom waveforms with and without visual feedback. (**B–E**) Averaged difference spectra from 4 subjects tracking low-frequency sinusoids (**B**, 0.04 Hz; **C**, 0.06Hz; **D**, 0.08 Hz; **E**, 0.167 Hz).

Figure 3). When the target was switched off, most subjects continued to track quite accurately. The two most obvious changes were a tendency for the responses to drift toward a lower frequency and errors in the maximum excursion required. The difference power spectra are shown in Figure 6. There was no significant difference in signal power between 0.3–2.3 Hz, and therefore no change in the degree of intermittency was seen in the tracking responses. There was a significant biphasic peak, however, close to the target frequency of 0.167 Hz. This was due to a shift, when the subject tracked from memory, of the principal component of the response to a frequency of about 0.15 Hz. Comparable difference spectra were seen in responses to target frequencies of 0.04–0.41 Hz (not shown). These results indicate that the subjects' responses to memorized waveforms were as intermittent as those to a visible waveform.

B. The Mechanism Underlying Intermittent Tracking

Experiment 3: Start and End Error Distributions

a. Pursuit and Compensatory Tracking

The distributions of positional errors measured at the start and end of each tracking movement are shown in Figure 7, giving the range ± 1 *SE* about the mean of the distributions from 6 subjects. These histograms illustrate sev-

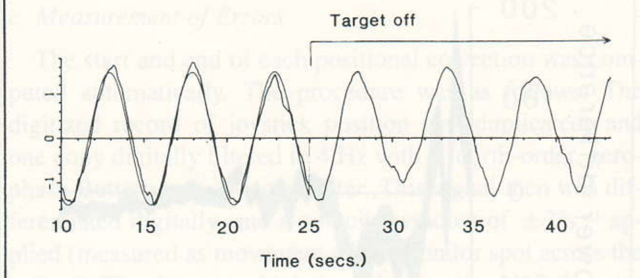

FIGURE 5. Typical tracking of a memorized 0.167-Hz sinusoidal target waveform. The light line indicates the target motion; and at 25 s, the target spot was switched off. Note that although the response tends toward a lower frequency, the track still shows evidence of intermittency.

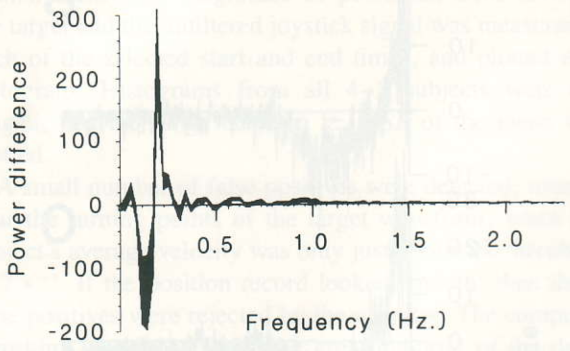

FIGURE 6. The average difference in the velocity power spectra when tracking a 0.167-Hz sinusoid before and after the target spot was switched off, forcing the subjects to track from memory. The area shown in black is ± 1 *SE* about the mean for 8 subjects. The individual spectra were calculated from the difference between power spectra of 25-s epochs of the velocity signal with and without the visible target. There is no significant difference in signal power above 0.2 Hz as the subjects switch to a memorized target function.

eral points. First, tracking was most accurate in the pursuit condition, with a very narrow distribution of terminal errors (Figure 7B, left). Tracking was least accurate, in terms of terminal errors, during compensatory tracking of the pseudorandom waveform (Figure 7B, right). Second, there was a pronounced peak in the distribution of errors measured at the start of each movement, seen most clearly in the histogram of compensatory sinusoidal tracking (Figure 7A, center). Hence, in both histograms from compensatory tracking (Figure 7A, center and right), most movements started only when the error had reached 0.8°, or 0.7 cm measured at the display screen. Few movements started with greater or smaller errors, and so these data are consistent with the idea that an error threshold or deadzone is responsible for the intermittency of the subjects' responses. The distribution of starting errors measured in the pursuit task showed only a small peak, however, and the clear majority of movements started with errors of under 0.8°.

The hatched areas in the upper histograms indicate the distribution of starting errors expected if the intermittent responses were due only to a refractory period of 170 ms between movements. These distributions were calculated from the distance that the target would move in each 170 ms period throughout each trial, by measuring the errors between the target and a version of the target lagging by 170 ms. In other words, we assumed for the purpose of this calculation that each movement terminated with zero error (as was approximately true: Figure 7B) and that the joystick then remained motionless until the subsequent movement started 170 ms later. This also assumes that each movement was of negligible duration; if movement durations were included, the sampling would be less frequent, but the distribution shape would not alter significantly. The shape is directly related to the absolute positional difference between the target waveform and its 170-ms time-lagged copy. Hence, the error at the start of the each new movement would be equal to the distance moved by the target in 170 ms. Although the figure of 170 ms gave the best fit between the hatched area (predicted errors) and the black area (observed errors), this fit was good only for the compensatory tracking data; the pursuit tracking errors were smaller than expected of this mechanism.

b. Compensatory Tracking at Different Frequencies

Figure 8 shows similar average distributions of the errors at the start and end of each positional correction as subjects tracked sinusoids at three frequencies. As before, the histograms of terminal errors were quite closely clustered about zero, indicating that the subjects were accurate in their tracking behavior. Terminal errors increased with increasing target frequency (Figure 8B, left to right), but even at the highest frequency tested, the majority of terminal errors were under 1.4° (or 6% of the target's maximum excursion). Thus, each corrective movement tended to finish close to the target, even though the target was continuously moving.

However, the distribution of the starting errors (Figure 8A), although again showing that relatively few movements started when positional error was below 0.5° (Figure 8A, center), spread as target frequency increased. The majority of starting errors lay between 0.9–2.8° at the highest frequency tested (0.2 Hz), clearly above the error deadzone estimated from Figure 7A. This argues against the deadzone hypothesis, at least one that assumes a fixed size of deadzone. Can the data be fitted better by an alternative mechanism?

As in Figure 7, the hatched areas indicate the distribution of starting errors expected if the intermittency was due only to a refractory period of 170 ms. The peaks of these predicted distributions fall approximately on the upper boundary of the observed distributions. Hence, the upper limit to the size of subjects' starting errors could have been influenced by a refractory period of about 170 ms measured from the end of the previous movement.

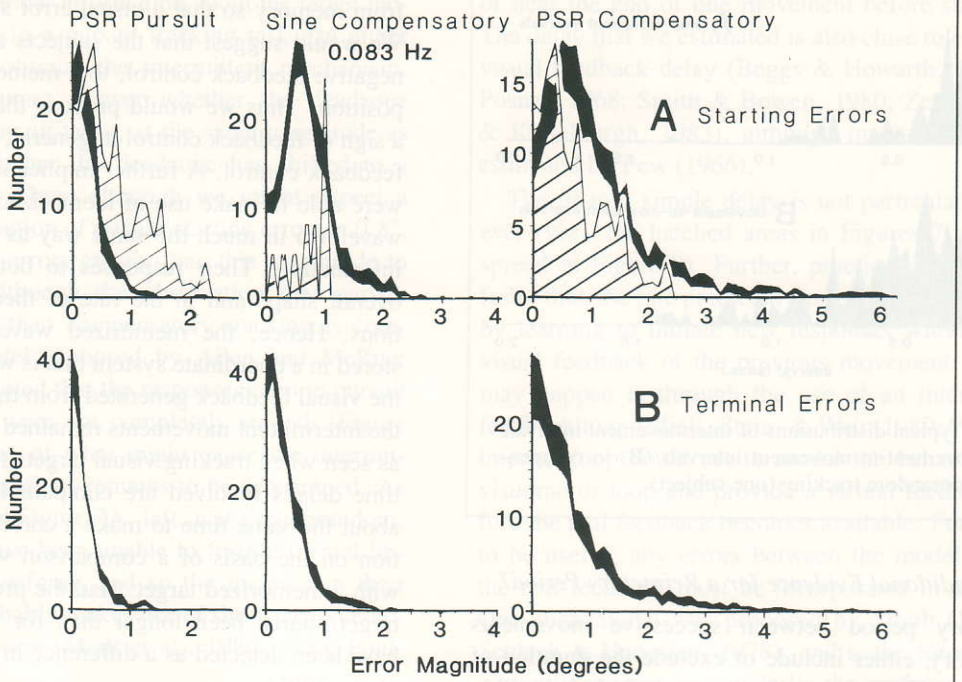

FIGURE 7. The average distribution of errors at the start (A) and end (B) of intermittent positional corrections in the tracking response. Errors are measured as degrees of visual angle at the subject's eye. Each black area is ± 1 *SE* about the mean of distribution from 6 subjects. The left and right graphs show responses when tracking a pseudorandom target, the center those when tracking a 0.083-Hz sinusoid. The hatched areas in the upper graphs indicate the distribution of errors predicted from a refractory or sampling mechanism with a period of 170 ms between movements (see text for details).

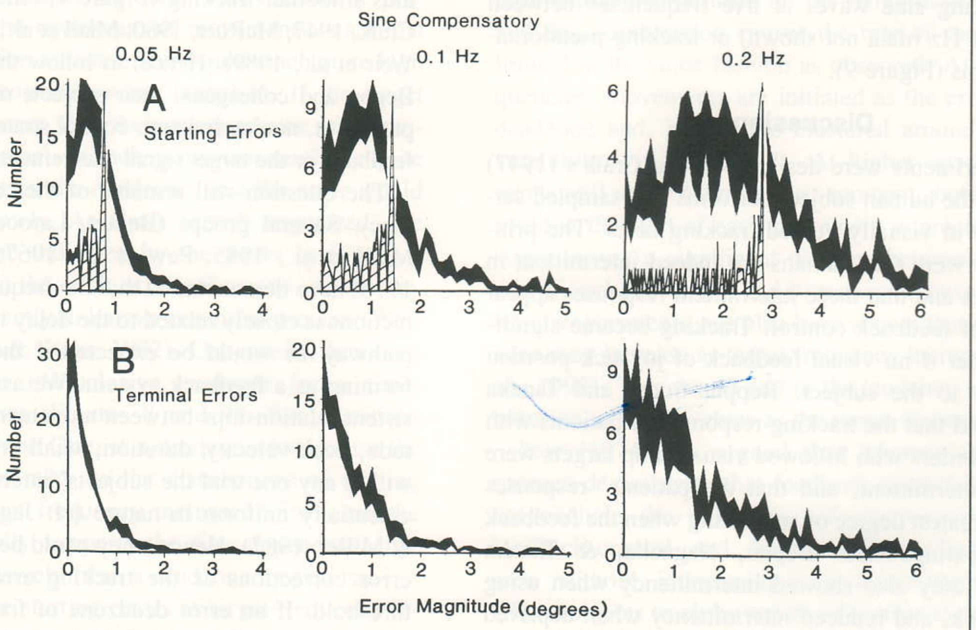

FIGURE 8. The average distribution of errors at the start (A) and end (B) of intermittent responses when tracking sinusoidal waveforms of various frequencies (left, 0.05 Hz; center, 0.1 Hz; right, 0.2 Hz). Each graph shows ± *SE* about the mean of distributions from 4 subjects. Hatched areas are calculated as in Figure 7.

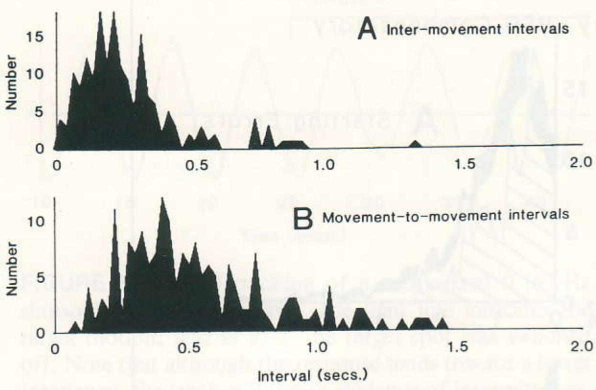

FIGURE 9. Typical distributions of intermovement intervals (**A**) and movement-to-movement intervals (**B**) in compensatory pseudorandom tracking (one subject).

c. Is There Additional Evidence for a Refractory Period?

A refractory period between successive movements could, in theory, either include or exclude the duration of the movements. If movement duration was included within a refractory period of fixed length, then one would expect that the time intervals from the start of one movement to the start of the next would be tightly distributed. A refractory period that was triggered at the end of a movement, an "intermovement" refractory period, would mean that the distribution of intervals from the end of one movement to the start of the next would be tightly distributed. No such clear peak in the distributions of movement-to-movement or intermovement intervals could be found in data from 2 subjects tracking sine waves at five frequencies between 0.04 and 0.41 Hz (data not shown) or tracking pseudorandom waveforms (Figure 9).

Discussion

These experiments were designed to test Craik's (1947) proposal that the human subject performs as a sampled servomechanism in visually guided tracking tasks. The principal findings were that humans are indeed intermittent in their responses and that these intermittent responses appear to be a sign of feedback control. Tracking became significantly smoother if no visual feedback of joystick position was available to the subject. Beppu, Suda, and Tanaka (1984) reported that the tracking responses of patients with cerebellar disorders who followed visual ramp targets were particularly intermittent, and that the patients' responses showed the greatest degree of smoothing when the feedback signal was extinguished (Beppu, Nagaoka, & Tanaka 1987). Thus, they also showed intermittency when using visual feedback, and reduced intermittency when deprived of visual feedback.

Next, we have shown that tracking remained intermittent even when the subjects were required to follow a memorized waveform. This implies that whatever mechanism is responsible for the intermittency of responses, it seems to operate whether the subjects track a visible target, or track from memory so that a visual error signal is not available. We would suggest that the subjects are nevertheless using negative feedback control, to a memorized record of target position. Thus we would propose that the intermittency is a sign of feedback control in general, rather than just visual feedback control. A further implication is that the subjects were able to make use of memorized records of the target waveform in much the same way as they employed visual information. Their responses to both were equivalent in overall shape and in the rate of their intermittent corrections. Hence, the memorized waveform is likely to be stored in a coordinate system that is wholly compatible with the visual feedback generated from the display screen. That the intermittent movements remained at the same frequency as seen when tracking visual targets further implies that the time delays involved are comparable: It apparently takes about the same time to make a correction of joystick position on the basis of a comparison with a visual target as with a memorized target. Had the processing delay for one target source been longer than for the other, this should have been detected as a difference in movement rate (Miall et al., 1985).

In contrast to our results, however, Beppu et al. (1987) found that tracking movements became smoother whether it was the target or the feedback that was extinguished. Their subjects' task was to follow a slow ramp of constant velocity, so they were probably able to form reliable predictions of its motion. We have shown that subjects' tracking corrections are planned using short-term predictions of target motion (Miall, Weir, & Stein, 1988), and it is generally accepted that additional information about target motion aids smoother tracking (Figure 7; Allen & McRuer, 1979; Craik, 1947; McRuer, 1980; Miall et al., 1986; Poulton, 1952; Weir et al., 1989). Hence, to follow the slow ramp used by Beppu and colleagues, their subjects may have shifted to a predictive, nonintermittent, control strategy when either visual feedback or the target signal was removed.

The question still remains of the cause of the intermittency. Several groups (Beuter, Larocque, & Glass, 1989; Miall et al., 1985; Pew et al., 1967; Smith & Sussman, 1970) have demonstrated that the frequency of tracking corrections is closely related to the delay in the visual feedback pathway, as would be expected if the subjects were performing as a feedback system. We assume, based on consistent relationships between movement parameters (amplitude, peak velocity, duration; Miall et al. 1986, 1988) that within any one trial the subjects' intermittent responses are essentially uniform in nature (cf. Jagacinski, Plamondon, & Miller, 1987). Hence, they could be the result of discrete error corrections as the tracking error exceeded a given threshold. If an error deadzone of fixed size were present within the feedback loop, then the distribution of start errors would be clustered approximately about the deadzone size (e.g., Figure 7A, center). Unlike a simple servomechanism, however, the degree of intermittency shown by human subjects can vary. The very narrow distribution of starting errors seen during pursuit tracking (Figure 7A, left) implies that the additional information about the target motion that is available in a pursuit tracking task can either avoid, suppress, or obscure the intermittent mechanism. Our present data cannot answer whether the deadzone might still exist in pursuit tasks, at the same magnitude as before (0.8°), or whether the deadzone has shifted to a much smaller value. Thus, although we might expect a shoulder to the distribution of pursuit starting errors at 0.8°, too few samples had errors greater than this magnitude to decide the point. Although the observation that pursuit tracking is smoother than compensatory tracking is compatible with the model proposed by Allen and McRuer (1979), it should be noted that the responses even in pursuit of sine-wave targets were not completely smooth (Figure 5). Thus, the question of what might cause the intermittency under these conditions remains to be determined. As the target waveform in Figure 7A, left, was pseudorandom, the subjects would have been unable to form a mental image of the whole waveform, and so the increase in their tracking accuracy probably makes use of short-term predictions about target motion (Miall et al., 1986, 1988; Poulton, 1952).

The third point to make is that the cause of the intermittent responses shows characteristics of both an error-magnitude dependent process (error deadzone) and a time-dependent process. For the moment, we need not distinguish in the time-dependent case between a refractory mechanism that inhibits new movements regardless of feedback (as detected by the double-step paradigms; Smith, 1967; Vince, 1947) and a pause as the subject waits to assess feedback of the previous movement (Pew, 1966). It seems possible that either of these time-dependent processes could limit the upper rate of movements, such that when the target motion is fast, errors could reach quite high levels before new corrections are launched. If the target motion is slow, however, then the error deadzone may dominate (Figure 7A, center), as each movement would be quite accurate, ending within the deadzone, and the error would only accumulate slowly. As Craik (1947) suggested, the size of the deadzone indicated by the peaks in Figure 7 (0.8°) is greater than the limit of visual acuity and so may be set by some presently unknown cognitive process (Wolpert, Miall, Winter, & Stein, 1992). Our results, however, provide only rather inconclusive evidence for a time-dependent mechanism (Figures 8 and 9). Two questions therefore need answers: One, if a deadzone does cause the intermittent behavior, why do the distributions of starting errors widen as target frequency increased? Two, can the evidence that partially supports the time-dependence hypothesis result exclusively from a deadzone mechanism?

The increase in the starting errors as target frequency increased may be approximately fit by a refractory period or delay of about 170 ms between the end of one movement and the start of the next. (Figures 7 and 8). This is close to the human reaction time in many visual tracking tasks (e.g., Poulton, 1974). This makes good functional sense, for it allows the subject time to appreciate his positional error at or near the end of one movement before starting another. The delay that we estimated is also close to estimates of the visual feedback delay (Beggs & Howarth, 1970; Keele & Posner, 1968; Smith & Bowen, 1980; Zelaznik, Hawkins, & Kisselburgh, 1983), although much less than the time estimated by Pew (1966).

The fit to a simple delay is not particularly good, however (viz., the hatched areas in Figures 7 and 8, and the spread in Figure 9). Further, practiced subjects can move faster than the rate predicted from the visual feedback delay, by learning to initiate new responses without waiting for visual feedback of the previous movement. One way this may happen is through the use of an internal predictive feedback loop (Miall, Stein, & Weir, 1989; Pew, 1974). An internal loop could act to model the behavior of the real visuomotor loop and provide a virtual feedback signal before the real feedback becomes available. For such a model to be useful, any errors between the model feedback and the real feedback must be incorporated in new responses. One such model was proposed by Smith (1957; see also Schleck & Hanesian, 1978), and is the form of model we currently suggest may underlie the performance of trained subjects (Miall, 1989; Miall et al., 1989). Analysis of this model, in which we postulate that feedback control is assisted by an internal predictive model and that movement corrections are limited by a positional error deadzone, has illustrated that the evidence of the time-dependent mechanism that we have shown here also can be produced by the model, without including any form of sampling or refractory mechanism (unpublished data). In brief, the model combines a deadzone and an inner feedback loop that contains a delay of perhaps 80 ms (Higgins & Angel, 1970), and this combination causes the rate of movements to be limited in the same fashion as observed. At low target frequencies, movements are initiated as the error exceeds the deadzone and, hence, are clustered around the deadzone amplitude (viz., Figure 7). At higher speeds, the movements still are initiated at that moment, but the error measured at the start of each movement is greater, because the target moves a significant distance between central initiation of each movement and its measured onset. In a separate set of experiments, we also have shown that the error deadzone may increase as target frequency increases (Wolpert et al., 1992). This would add to the tendency to shift the distribution to larger values as the target frequency increases.

Pew (1974) has argued that whereas intermittent responses demonstrate that feedback control is used, it does not exclude the possibility of continuous underdamped feedback control, and, hence, the same features might be seen without introducing any intermittent mechanism. Often subjects track by means of a clear staircase of movements, however (e.g., Figure 1), which does not fit well the sort of smooth hunting behavior shown by underdamped controllers.[1] From the results presented here and in Wolpert et al. (1992), we believe a discontinuous, nonlinear process to be more likely than continuous control. The main advan-

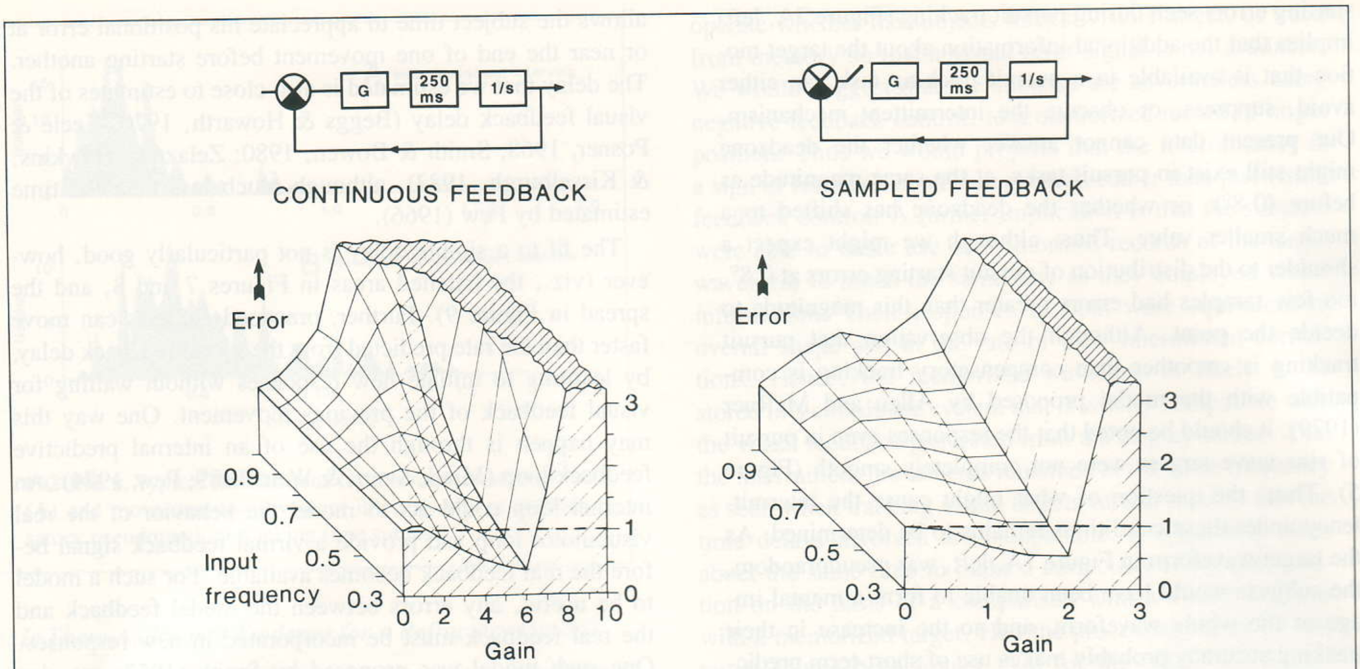

FIGURE 10. The performance of a simulated servomechanism is influenced by target frequency and servo gain. The continuous servomechanism (left) has a characteristic sharp border (at gain = 6) between optimal performance and instability (where errors accumulate toward infinity). The performance of a sampled servomechanism (right) has a broader band at which near-optimal performance is achieved, allowing a wider safety margin away from instability. Both graphs are from a digital simulation of a servo-control system, iterated with 10-ms resolution and driven by a sinusoidal input. The servo model consisted of a positional error comparator, an error-gain term (G, see diagram at top), a time-delay of 250 ms, and an integrator. The sampling model (right) also included an error sampler that evoked a discrete velocity pulse via the delay and integrator once every 250 ms. For each model the servo's positional error was summed over the first 10 s of each trial, and plotted relative to the error expected if the servo was inactive (scaled to unitary error at zero gain, see dashed line in front of each graph). High error values were truncated for clarity.

tages of discontinuous control are that the control system is not active unless errors are significant, and, perhaps more important, that breaking the feedback pathway greatly improves the stability of the servo system, because errors cannot accumulate (e.g., Doebelin, 1985). This is shown in Figure 10, in which the cumulative error of a simple servo device is plotted against the input frequency and the open-loop gain of the servo (details of the computer simulation are given in the legend). As is well known, servos operate best when their open-loop gain is set as high as is compatible with the transport and dynamic delays within their feedback loop. Thus as open-loop gain was increased in Figure 10A, the error score was reduced. As soon as the gain exceeded the optimal value, however, the servo became unstable, and accumulated errors shot off toward infinity. Of course, in reality any such system would reach mechanical or energetic limits, so that errors would be high but not infinite.

If the same system now is set to operate intermittently, however, by sampling the input error at an interval just longer than the response time of the servo, the situation improves greatly (Figure 10B). The very narrow region of optimal behavior seen in Figure 10A widens, so that good performance can be achieved without the gain's being set dangerously close to the instability boundary. If there were any uncertainty in system performance, as is likely in biological control systems, then this configuration would be much safer than continuous control.

A second possible advantage of intermittency is that it could assist in characterizing the dynamics and delays of the limb. Internal or predictive feedback through a mental model of the controlled system can avoid the handicap of long feedback delays (Miall, 1989; Miall et al., 1989; Smith, 1957). To be successful, of course, the internal model must be accurate. One way that the brain could identify the dynamics involved would be to inject wide-band noise into the system and monitor the feedback. The "command pulses" sent to the arm during intermittent tracking could serve this purpose. Further, by causing step-like changes in arm position, they help to identify more clearly the loop delays, because the CNS could effectively monitor the time interval between issuing a command and seeing the response. Some test pilots are thought to "jitter" the controls of airplanes for much the same reasons.

In summary, then, we have presented data suggesting that the intermittency appears to result from an error deadzone. There is some evidence that a time-limiting process, due either to a refractory period or to a delay to access visual feedback, also contributes to limit the rate of movements, but whether it is a necessary element of human tracking performance seems to us still open to question.

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NOTE

1. It has been suggested that we simulate the subjects' responses to test whether a continuous model that has neither a deadzone nor a time-dependent process could result in the observed intermittency. Intermittency is unlikely to result from the hunting of a continuous linear servo device, however, for the device would be very sensitive to the servo parameters. Hunting could be a stable behavior if the servo contained significant nonlinearities, for example, error signal saturation; but we have no evidence for such nonlinearities. Furthermore, desired results always can be obtained if constraints on a model are weak enough. In other words, there almost certainly will be some continuous model that approximates the data well enough. In contrast, even very simple discontinuous models do seem to adequately fit the data.

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