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Task-Dependent Changes in Visual Feedback Control: A Frequency Analysis of Human Manual Tracking

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ABSTRACT. Prominent components in the frequency spectrum of human manual tracking responses are thought to reflect the visual feedback control loop and have been used in estimations of the visual feedback loop delay. The frequency structure of human tracking was therefore examined here in two tasks: visually guided tracking of slow and fast pseudorandom targets. Visually related frequency components were identified by testing, in each condition, the effect of adding additional feedback delays on the frequency spectrum. The major frequency components of the responses consisted of a fundamental component and its odd harmonics. These components were related to the visual feedback loop delay and shifted in concert toward lower frequencies as the feedback delay was increased. Furthermore, there were no differences in responses between 3 normal subjects and 1 subject with peripheral sensory loss. This implies that the frequency structure is dominated by the visual feedback control loop, without significant influence from proprioceptive control loops. However, the feedback-loop delay was shown to decrease from around 341 to 264 ms as the task speed doubled. Thus the estimates of visual-feedback delays are influenced by the target being followed, and this suggests that the subjects can "tune" their feedback system to suit the demands of the tracking task.

Key words: feedback delay, human, manual tracking, proprioception, spectral analysis, visual feedback

The responses made by primates—human or monkey—during manual tracking tasks are quite characteristic. If the task is easy enough, for example, human pursuit tracking of a reasonably slow sinusoidal target, then the responses are indistinguishable from the target waveform. They are smooth, accurately scaled, and have virtually no lag (Weir, Miall, & Stein, 1989). If the task is more difficult—for example, if a monkey tracks the same sinusoidal target or a human tracks a pseudorandom waveform—then the responses become less smooth and lag behind the target. This behavior has been called *sampled* or *intermittent* tracking (Craik, 1947; Miall, Weir, & Stein, 1986), and although there is still discussion about the causal mechanism, I use the term *intermittent* here without implying any particular mechanism (cf. Miall, Weir, & Stein, 1993; Wolpert et al., 1992). The intermittent responses occur about 1–2 times per second, and frequency analysis of the records shows a band of components lying between these frequencies (Miall et al., 1986; Pew, Duffendack, & Fensch, 1967a). It seems probable that they are a sign of visual control of the movements; I and others have suggested that they are a signature of the visual feedback control loop (Miall, Weir, & Stein, 1985).

However, the frequency spectra of human movement records include peaks other than the primary one at 1–2 Hz (see, e.g., Marsden, 1984). A band at 8–10 Hz has been attributed to physiological tremor, and may reflect the operation of a proprioceptive control loop. Other bands are seen that are less clearly related to particular control pathways. For example, a band at about 3–4 Hz may be related to tremors seen in motor disorders (especially of the cerebellum), or it may simply be higher harmonics of the lower bands. One of my aims in this experiment was to clarify the significance of these spectral components. To do this, I used delayed visual feedback, a procedure that is known to affect the frequency structure of visually guided tracking.

The responses of simple feedback control systems to changes in the feedback delay can be informative. For example, the stability of the system is indicated by its tolerance of increased delays. If the system responds intermittently to an increased delay or oscillates about the target

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value, then the period of the responses can predict the total loop delay and, thus, also the intrinsic loop delay. The 1- to 2-Hz band of frequencies seen during visuomotor tracking move to lower frequencies if the total delay in the visual-feedback loop is experimentally increased (Beuter, Larocque, & Glass, 1989; Miall et al., 1985; Pew et al., 1967a) and the intercept corresponding to zero delay is about 400–450 ms. Thus, clearly these frequencies are related to the visual-feedback-loop delay, which is generally assumed to be of about half that magnitude (Keele, 1981; Poulton, 1974). Furthermore, the slope of the relationship between the period of response oscillation and imposed delay may indicate the dynamic behavior of the control system itself. A linear system should have a slope of 2 (see Discussion), whereas nonlinear controllers may have higher slopes (Glass, Beuter, & Larocque, 1988). Thus, the frequency responses can characterize the control loop and constrain models of the control system.

One can also examine how the higher frequency bands behave during delayed feedback. If they shift together with the 1- to 2-Hz band, then they could well be harmonically related to the lower band. Hence, by using delayed visual feedback tracking, one can test whether a particular frequency component is influenced by the visual control loop. Frequencies that do not shift could represent power in separate control loops that are unaffected by the changes to the visual feedback loop. As a further test of the relative contribution of visual and proprioceptive feedback loops to the frequency structure of human manual tracking, I also contrasted normal control tracking with tracking performed by a patient with peripheral deafferentation, a condition that effectively abolished his proprioceptive-feedback pathways.

In this study, I have therefore reexamined the frequency composition of manual tracking records in normal subjects and in a deafferented subject, tracking at two target speeds and with artificially delayed visual feedback. The dependence of the frequency components on these variables provides clues to their origin and limits the possible control strategies.

Method

Subjects

Four subjects were tested. Three were right-handed males with no known neurological abnormalities. All three were members of the laboratory and were experienced in these tracking tasks. Comparison of their tracking responses with those of less experienced subjects (unpublished) indicated that the experienced subjects used in this study were more consistent in their responses from trial to trial. Hence, although their tracking tended to be somewhat more accurate and smoother, the frequency components in the responses were more sharply localized within frequency spectra. The major features of the responses of the 3 subjects were nevertheless similar to those of less experienced subjects. One deafferented male subject (I.W.) was also tested on the same tasks. He has peripheral large fiber sensory neuropathy that has been stable for many years, with negligible sensation below the shoulder and none from the wrist or hand but with intact motor function (Cole & Sedgwick, 1992).

Task

A subject sat before a computer monitor on which a target was displayed as a small hollow square (4 × 4 pixels, approximately 0.13 × 0.2° at the eye). The right forearm was supported in an adjustable plastic channel, which was adjusted for each subject so that the wrist was held firmly. The subject held in his right hand a manipulandum that allowed only flexion and extension of the wrist. The manipulandum rotated freely, and its position was recorded by a light, high-quality potentiometer. The voltage signal was low-pass filtered to 25 Hz and digitally sampled with 12-bit resolution at 60 Hz. The angular position of the manipulandum was displayed as a small cursor (2 × 2 pixels), which could move horizontally across the computer screen at the same level as the target. The subject's task was to use compensatory tracking to keep the cursor as near as possible to the target.

The track waveform (which in compensatory tracking displaces the cursor away from a stationary, centrally placed, target) was a pseudorandom function made from the summation of four equal amplitude sinusoids, moving a maximum of 600 pixels across the screen (20°). Two target speeds were used. The faster had component frequencies of 0.16, 0.24, 0.40, and 0.55 Hz; for the slower track, these frequencies were halved. Subjects needed to flex–extend the wrist 60° to match the full excursion of the target.

The cursor could reflect the manipulandum position directly, or a time delay could be inserted between manipulandum movement and corresponding cursor movement. Delays of 0 (control), 116, 167, and 250 ms were tested. Normal subjects were tested over five daily sessions of eight trials, tracking at both target speeds and with all four delays. Each trial lasted for 100 s. The order of the trials was randomized in each session.

Subject I.W. was tested on 1 day, using slightly different computer equipment for display and data capture. The dimensions of the target display and the target frequencies were identical, but the refresh rate of the screen was 70 Hz, and each trial lasted only 50 s. Delays of 0, 57, 114, 171, and 228 ms were tested for both the fast and slow targets (total 10 trials). I.W. first used his nonpreferred right hand for all 10 trials and was then given approximately 1 min practice with his preferred left hand before repeating all 10 trials. Only data from his preferred hand are reported here; tracking was poor when he used his nonpreferred hand.

Data Analysis

Target and cursor positions (Figure 1) were recorded by the computer for subsequent analysis. The root mean squared (RMS) tracking error was calculated for each

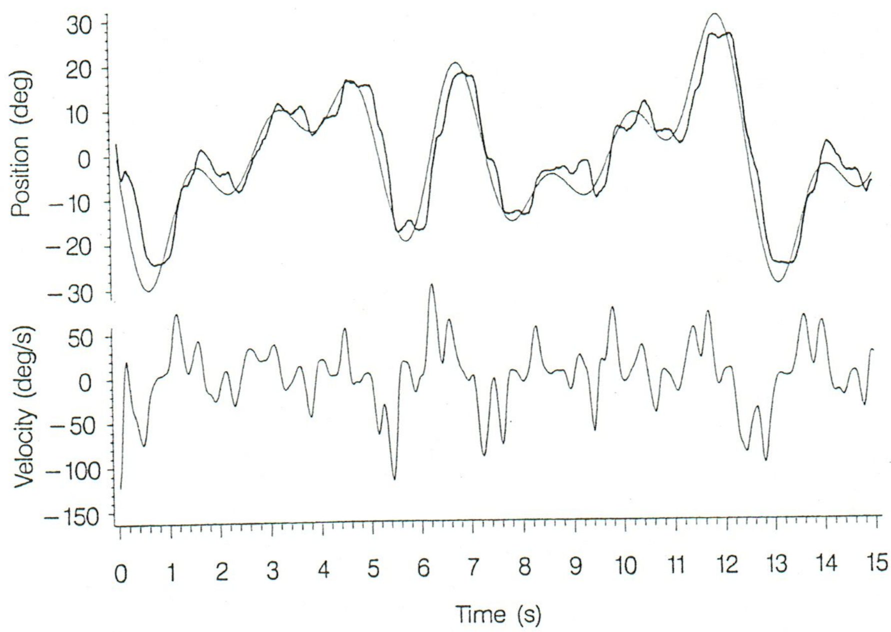

FIGURE 1. Typical compensatory responses of 1 subject (Subject 1) tracking the fast pseudorandom target. The upper traces show the underlying target waveform (thin line) and the cursor position (thick line). The lower traces show the cursor velocity calculated from the position record and then, for display in this figure only, low-pass filtered to 5 Hz. All amplitude spectra were calculated from velocity records filtered at 25 Hz.

record, excluding the first second of each trial. I then digitally differentiated the position records to velocity to emphasize their higher frequency components. The amplitude spectrum of each velocity record was then calculated by Fast Fourier Transform (100-s data = 6,000 samples, padded with zeros to 8,192 points). The positive differences between the cursor and target spectra were then calculated over the range 0–22 Hz, representing the subject's responses excluding all target frequencies (Figure 3). These difference spectra have rather poorly defined bands of power between 1–2 Hz and at other frequencies. The sharp peak shown at 9.8 Hz in Figure 3 resulted from aliasing by the 60-Hz sampling rate of a small 50-Hz mains ripple introduced by the digitizing amplifiers. Differentiation from position to velocity scales the amplitude of spectral peaks in proportion to their frequency, however. Thus, although it is prominent in this velocity spectrum, the peak corresponded to a positional component of only 0.5 pixels (or < 1% of the positional signal). Furthermore, because the peak was present in all spectra, it was easily distinguished from valid peaks within the signal.

To localize the frequency bands lying between about 1 and 8 Hz, I smoothed the spectra by passing them through a zero-phase fourth-order digital filter (forward and backward passes through a second-order filter). Peaks in each smoothed spectrum (Figure 4) were localized by using an algorithm detecting reversals in the waveform and were

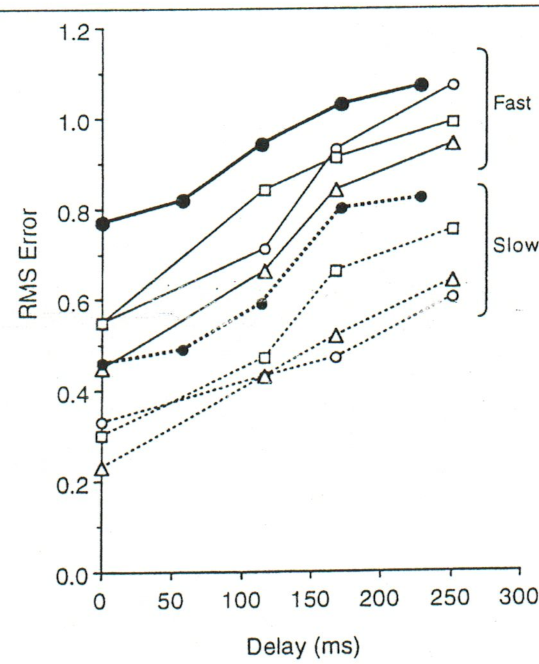

FIGURE 2. The mean RMS error score per subject across all delays and with two target speeds. The RMS scores are in arbitrary units. Hollow symbols represent data from normal subjects; solid symbols, data from deafferented Subject I.W. Solid lines = fast target condition; dashed lines = slow target.

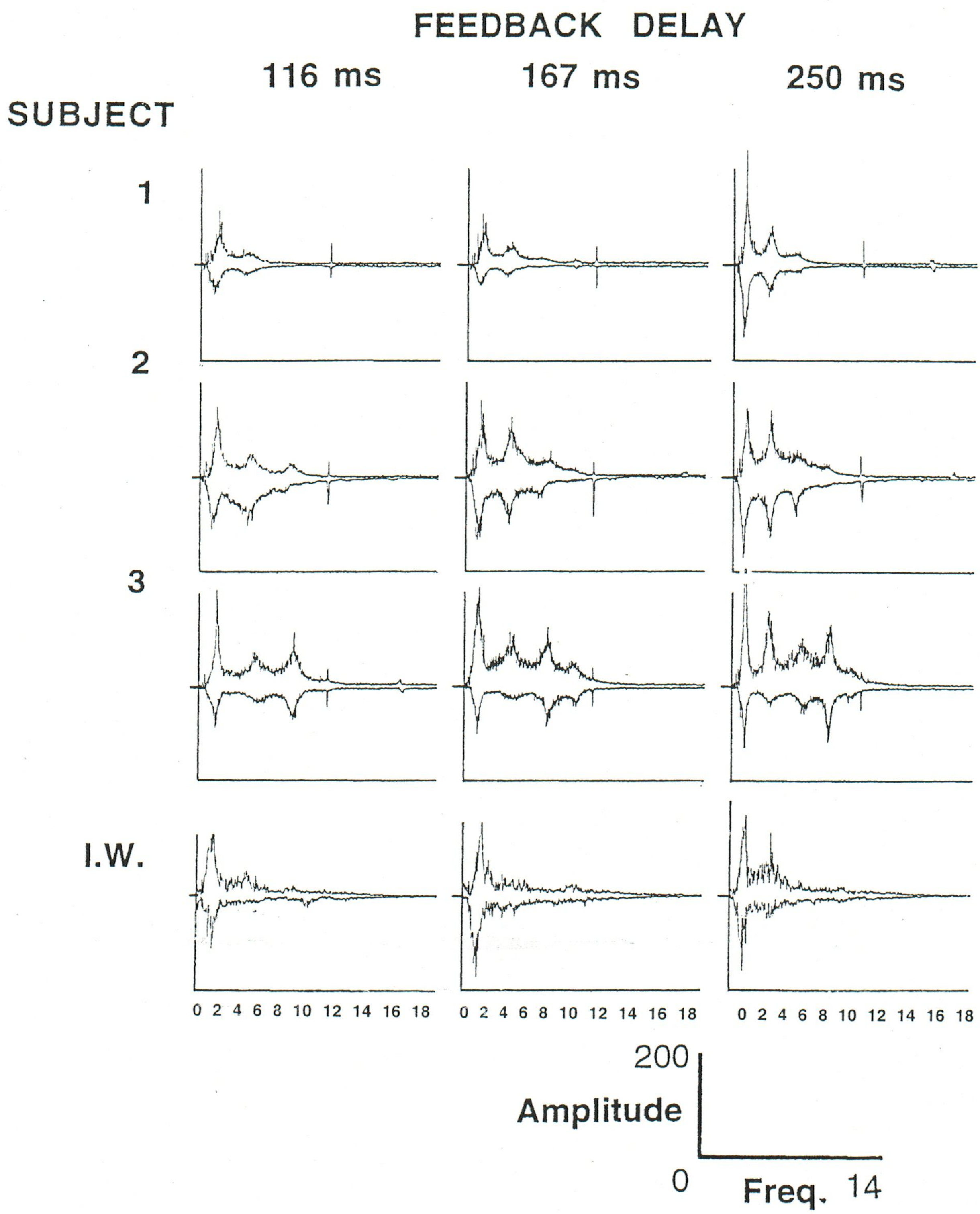

FIGURE 3. Average difference spectra for each subject at three feedback delays and for two target speeds. Each panel shows two mean spectra, averaged over five individual difference spectra calculated from the amplitude spectrum of the response velocity and the target velocity on each of five trials. The upper trace in each panel is for the fast target; the inverted lower trace is for the slow target. Because of the overlap in their frequency content, the spectra have been offset vertically and plotted as "mirror images"; the vertical axis is in arbitrary units. The data from Subject I.W. (bottom row) were not averaged, because he tracked each target only once for each feedback delay. Also, for this subject, the feedback delays tested were 114, 171, and 228 ms.

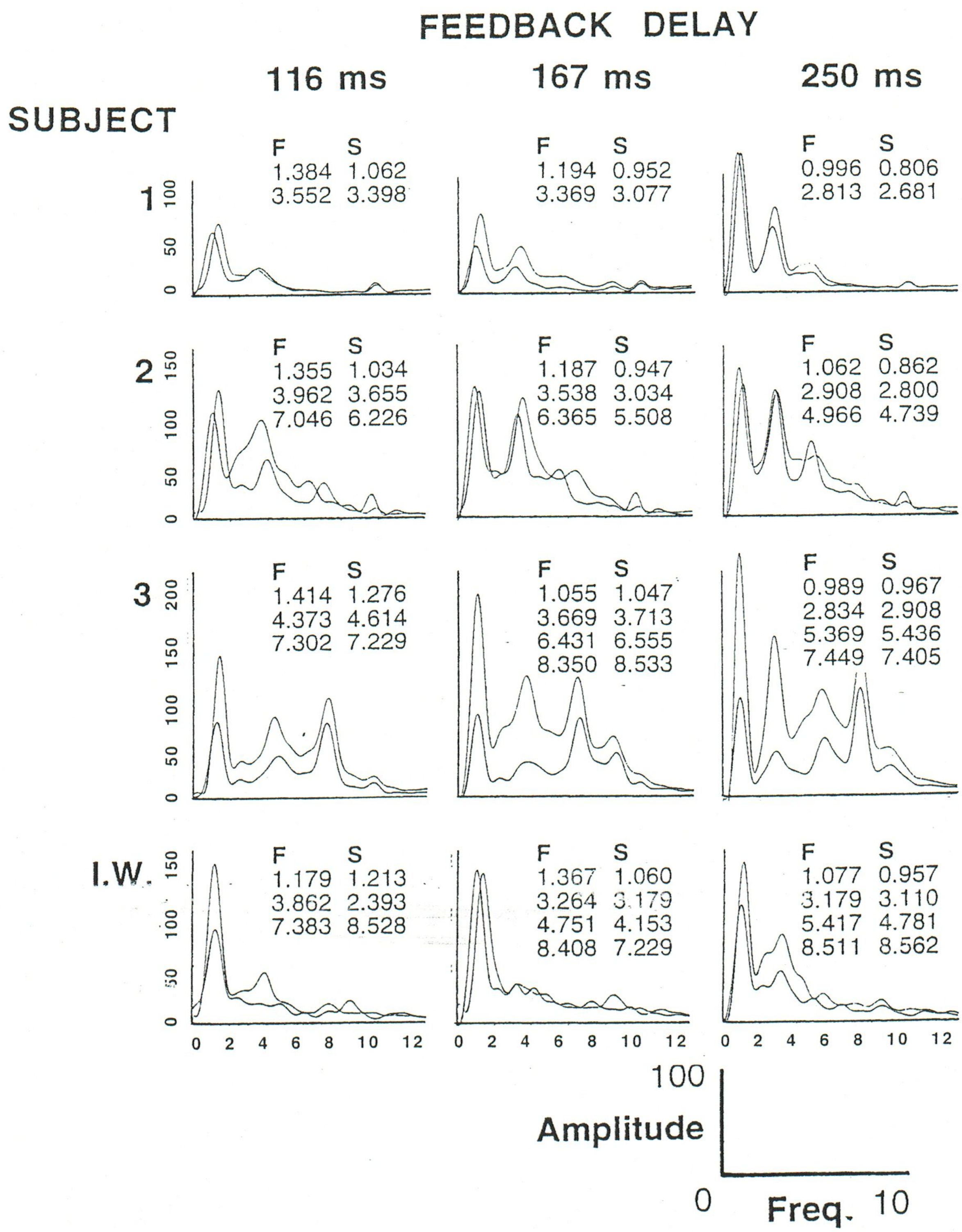

FIGURE 4. Smoothed difference spectra for each subject at three feedback delays and for two target speeds. Each panel shows two averaged difference spectra, taken from the corresponding panels in Figure 3 and smoothed with a zero-phase digital low-pass filter. The frequencies of the major peaks in each record are given in Hertz for the fast (F) and slow (S) tasks, found with a simple algorithm (see Method). The data from Subject I.W. were not averaged but were calculated from individual trials.

then taken to represent the center of each frequency band. The number of peaks found by this technique depends critically on the amount of smoothing applied. Smoothing should not change the location of the peaks, however. Thus, a constant level of smoothing was chosen for all data, such that the peak detection algorithm reported a single peak between 1–2 Hz, when applied to any typical control tracking spectrum.[1] This level was equivalent to an upper frequency cut-off of 1.0 cycle/frequency as applied to a frequency series.[2]

The period of each peak found was then plotted against the imposed feedback delay for all five trials from each subject (Figure 5). A linear regression of the period of the peaks upon the imposed delay was also calculated.

Results

All 4 subjects were able to accurately track the target waveform at either the fast or slow speed. A typical trace is shown in Figure 1. Note the subject's intermittent step-like approximation to smooth movement (e.g., at 6.5 and 7.5 s) and his failure to follow small changes in target position (e.g., at 8.5 and 12 s).

The RMS tracking errors were, as expected, higher for the fast target condition than for the slow target and rose progressively as the feedback delay increased (Figure 2). A factorial analysis of variance indicated that the RMS error for each subject was significantly influenced by task, $F(1, 92) = 694.9$, $p \leq .0001$, and delay, $F(3, 92) = 241.6$, $p \leq .0001$, and that there were significant intrasubject differences, $F(3, 92) = 54.1$, $p \leq .0001$. In particular, the deafferented subject had RMS errors about 50% greater than the normal subjects at zero delay, falling to 10–25% greater errors at the maximum delay. There were no significant interaction effects.

Frequency Analysis

All 3 normal subjects followed the target waveform with a series of quite discrete positional corrections (Figure 1). Hence, the spectra were characterized, as expected, by a band of frequencies at 1–2 Hz (referred to hereafter as the *primary peak*; Figure 3). Each spectrum also contained additional peaks lying between the primary peak and the upper limit of signal power at about 10 Hz (Figures 3 and 4). These peaks were quite clear in the averaged spectra (Figure 3, Subjects 1–3); in the individual spectra calculated from each trial, the peaks were less clearly localized. The individual spectra from Subject I.W. (bottom row, Figure 3) are typical of the individual spectra calculated from the other subjects' responses. Figure 4 shows the same spectra as in Figure 3, after smoothing by digital filtering. The basic forms of the spectra were unchanged by the smoothing, but the frequency location of each peak was then measurable. The responses to the faster target waveform were noticeably smoother than those to the slower target, and the primary peak was smaller and shifted toward a higher frequency (Figure 4). As above, comparison of the individual-trial spectra from Subject I.W. with the averaged spectra of the other 3 subjects gave some idea of the intertrial variability.

The Effect of Feedback Delay on Tracking

The primary peak shifted toward lower frequencies as the feedback delay was increased, as expected. The secondary peaks seen in the averaged spectra (Figure 4) also shifted toward lower frequencies and in most cases were close to the expected position of a third or fifth harmonic of the primary peak. In the individual spectra, the location of secondary components was less clear, and the computer algorithm used to detect peaks found a number of small peaks at frequencies up to 10 or 12 Hz. Although not all of these fell on odd harmonics of the primary peak, those that did not were of small amplitude. Figure 5 shows the location of every peak found in all spectra, plotted as period rather than frequency. There was an obvious and linear relationship between the period of the primary component and added delay. Figure 5 also shows how some of these secondary components appeared to fall along lines with slopes shallower than those of the primary components.

Unfortunately, to attempt to fit regression lines to these data (Figure 5), one would need to group together corresponding sets of secondary peaks at each different delay. It is not clear, however, which component within any one spectrum should lie on which regression line. For example, what appears to be the second peak within a spectrum, and hence should be tested as a third harmonic, might fit more closely to the fifth component if the real third harmonic was very small. No statistical technique for categorizing these components was found, other than optimizing four or more regression equations simultaneously and testing every combination of clustering the data points to the four individual lines (potentially 6×10^{46} possible combinations). As an alternative, a linear multiple regression equation was calculated, subject by subject, from the data in Figure 4. The dependent variable was the frequency location of the peaks in each curve (which are printed in Figure 4); the independent variables were the harmonic numbers (1, 3, 5, and 7), the reciprocal of the feedback delay, and a dummy variable coding for task (fast or slow tracking). The 12–22 frequencies observed for each subject were very reliably fitted by this linear model (for the 3 controls, $r^2 \geq .98$, $p \leq .0001$, RMS error ≤ 0.37, $F \geq 199$; for Subject I.W., $r^2 = .91$, $p \leq .0001$, RMS error = 0.91, and $F = 58.22$). The partial F ratios for the contribution caused by the harmonic series ranged from 173 (for Subject I.W.) to 1,074 ($p \leq .0001$). This suggests that these peaks were indeed very close to those that would be expected if they were all odd harmonics and all moved in tandem as the feedback delay increased.

The Effect of Target Speed on Tracking

The responses from the 3 normal subjects were analyzed separately from the responses of the deafferented subject, because of the restricted amount of data available for him (to be discussed later). When the period of the primary peak was plotted against imposed delay, the regression lines for the two target speeds were parallel but clearly separate (Figure 5). The six regression lines (3 subjects at two target speeds) were all highly significant ($r^2 \geq .844$, $p \leq .001$). None had a slope significantly different from two. By using a linear regression model with a dummy variable coding for

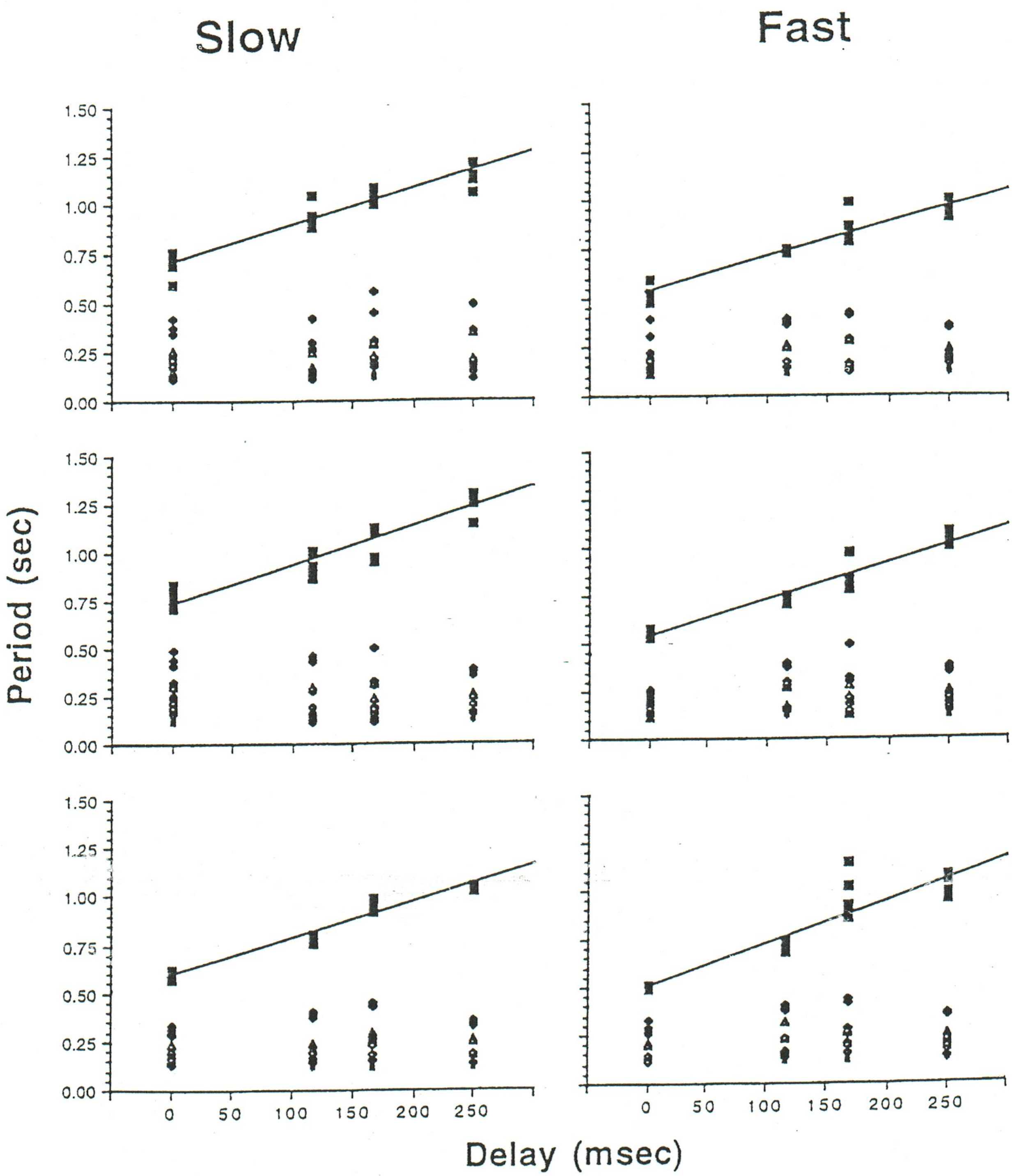

FIGURE 5. Scattergrams of the period of tracking components against imposed feedback delay for each subject. The three panels on the left are from the slow tracking task; those on the right are from the fast task. In each, a linear regression line has been fitted to the first (primary) component in each spectrum. Note that the regression lines are all parallel but that the y-axis intercepts of those for the fast task on the right are lower (i.e., of lower period or higher frequency) than those for the slow task.

the two target speeds, it was shown that for each subject the pair of regression lines did not significantly differ in slope ($p \geq .19$–0.68) but had significantly different intercepts ($p \leq .0001$–.023, Table 1).

The number of secondary peaks detected did not significantly differ between fast and slow target speeds or between trials with different feedback delays ($p \geq .76$, chi-square, n = 16–27); nor did the distribution of their frequencies differ between the two tasks, either when data were grouped across all feedback delays ($p \geq .34$, Mann–Whitney U test, $n \geq 75$ per task per subject) or at any one delay ($p \geq .11$, Mann–Whitney U test, $n \geq 15$ per task per subject).

The Effect of Peripheral Deafferentation

The deafferented subject, I.W., has been shown to have no knowledge of his wrist position when his forearm is carefully supported in the channel (Cole & Sedgwick, 1992; Miall, Haggard, & Cole, 1995). Nevertheless, given visual feedback of the manipulandum angle as a cursor on the screen, he was able to track the target waveforms with reasonable accuracy. The tracking responses he made while using his preferred hand were qualitatively similar to those of normal subjects, although the RMS error scores of his tracking were significantly higher than those of the 3 normal subjects ($p \leq .0001$; Figure 2). However, there was no clear link between tracking performance measured as RMS error and the spectral distributions (comparing across subjects in Figures 3 and 4).

His responses were analyzed in the same fashion as those of the normal subjects, and a scatter plot of the period of tracking components against added feedback delay is given in Figure 6A. This plot shows all peaks located within each difference spectrum; because there was only a single trial per tracking condition, no regression analysis was performed. It is clear, however, that the major features of the results from normal subjects were also found in this subject: The peaks were located at shorter periods in the fast tracking task; the peaks were proportional to imposed feedback delay, with a slope very similar to that of the normal subjects; and the higher frequency components were distributed in much the same manner as before. The plots of peak period against delay were much less regular when he used his nonpreferred hand (not shown), but his tracking errors were also significantly higher.

In Figure 6B, plots of theoretical data show the expected shift of a fundamental frequency and its odd harmonics with

TABLE 1
Regression of Primary Component Period on Imposed Delay

Subject	Target speed	Regression slope	Intercept (ms)	R^2
1	Fast	1.7126	539 } **	.911
	Slow	1.8450	711	.904
2	Fast	1.8783	539 } **	.934
	Slow	1.9860	738	.886
3	Fast	2.1682	506 } *	.844
	Slow	1.8480	597	.955
M (n = 3)	Fast	1.9197	528	
	Slow	1.8930	682	

Note: Asterisks indicate intercepts that were significantly higher for fast tracking than for slow tracking, for each subject ($^*p < .025$; $^{**}p < .01$).

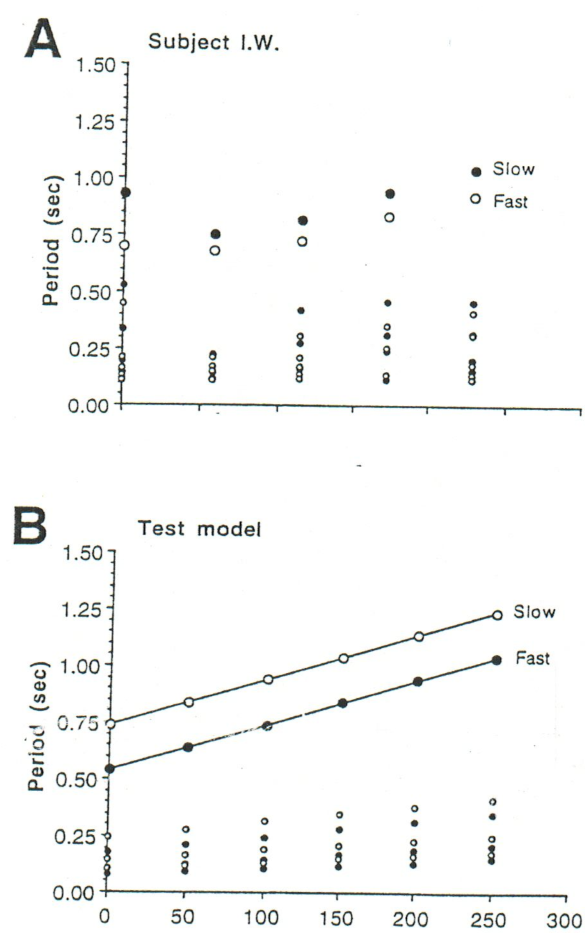

FIGURE 6. A. Scattergram of the period of tracking components against feedback delay for Subject I.W. Because of the limited amount of data, no regression lines were plotted. **B.** Expected change in period of a fundamental component of a loop as its feedback delay increases, plotted with its 3rd, 5th, and 7th harmonics. The period of the primary component was taken to be twice the external feedback delay plus either 528 ms for the fast tracking task (hollow dots) or 682 ms for the slow tracking task (filled dots) so that the average intercepts would match those given in Table 1.

increasing feedback delays. The graph shows two sets of data, in which a fundamental frequency has been set with the same mean period as that observed in the fast and slow tasks in the 3 normal subjects tracking at zero delay (i.e., the average intercept given in Table 1). The other data points in this graph are the periods of the third, fifth, and seventh harmonics calculated from these two primary peaks. The two solid lines then show how these two primary peaks would shift if their periods were increased by twice the added delay (i.e., each line has a slope of 2.0). The other points show how the odd harmonics also shift with delay, with slopes of 2/3, 2/5 and 2/7. This figure has been presented as an indication of the close fit between the expected location and the shift of the primary peak and its odd harmonics with the peaks observed in our subjects (Figures 5 and 6A).

Discussion

There are three points to make about these results.

First, the majority of signal power in the records of human visuomotor tracking, calculated by using the difference spectrum to exclude components from the target, is related to the visual feedback loop time. The primary peak, lying between 1–2 Hz, shifts systematically to lower frequencies as the delay is increased. This result has now been well documented (Beuter et al., 1989; Miall et al., 1985; Pew et al., 1967a). It is also clear that most of the higher frequency components with significant power are likely to be higher harmonics of the primary peak. They correspond to the odd harmonics of the primary peak and remain harmonically related as it shifts with added feedback delay. The odd harmonics result from the inherently intermittent nature of the tracking. This confirms the report of Pew et al. (1967a); a similar shift of the odd harmonics of a 3-Hz peak has been seen in tremor of the hand (Merton, Morton, & Rashbass, 1967). Together these peaks account for the major features in the frequency spectrum between 1 and 8 Hz. Note that the spectra displayed here (Figures 3 and 4) were calculated from the velocity records. Hence, high-frequency components were emphasized and actually contributed progressively smaller amounts to the power of the positional signal. Given the spread of power about each frequency component, which is very typical of human tracking data, it is therefore clear that the majority of the signal power in these difference spectra was visually related. However, the present results also showed that the frequency composition of tracking recorded from a subject with no proprioceptive input was essentially identical to that of the normal subjects. This gives further support to the view that these frequency peaks are a signature of the operation of the visuomotor control loop. Only in 1 of our subjects, Subject 3, was there evidence of a significant nonvisual component. In this subject, there was a peak at about 8 Hz that was not harmonically related to the other peaks (most clearly visible in the central column, third row, of Figure 4). This component did not differ in frequency location between the two tasks and may therefore have been dependent on proprioceptive inputs. The spread of signal power about each harmonic component resulted from several factors: variations in intermittent rate as the pseudorandom track was followed (Miall et al., 1985, 1993), a minor effect of calculating spectra from records of less than infinite duration, and possible contributions from learning or fatigue. As mentioned previously, I chose experienced control subjects to limit these latter factors, and there were no systematic time-dependent effects for the deafferented subject. Thus, although these conclusions are based on a small sample, and although I cannot exclude all contribution of proprioceptive control to the tracking responses, it appears that the frequency structure of tracking behavior is dominated by visual control.

Second, the slope of the regression between the period of the primary peak and the imposed delay was not significantly different from a value of 2.0. A simple feedback system will spontaneously oscillate at the frequency at which the open-loop phase lag is 180° (Mackey & Glass, 1977; Wolpert, Miall, Kerr, & Stein, 1993). The phase lags arise from the phase shift Ø because of intrinsic dynamic properties, from intrinsic pure time delays T_{int} and from externally imposed time delays T_{ext}. The period of the oscillation p can be determined by converting the pure time delays into phase lags in degrees, so that

$$Ø + (360T_{int})/p + (360T_{ext})/p = 180°.$$

Thus,

$$p = 360(T_{int} + T_{ext})/(180 - Ø).$$

So, the period is related to the externally imposed delay, with a slope of 360/(180 – Ø) and with an intercept of $360T_{int}/(180 - Ø)$ ms. The slope for all our subjects was very close to 2, and the intercept was close to double the estimates of human visual reaction times (Beggs & Howarth, 1970; Keele & Posner, 1968; McLeod, 1987; Pew, 1974). Hence, the intrinsic dynamics do not appear to contribute significantly to the feedback system's phase delay (i.e., Ø = 0). As we know that the visuomotor loop does have quite complex dynamic properties, this implies that there may be effective compensation for much of the motor system dynamics; for example, by a predictive component of the control system. It should be clear, of course, that the human operator is not a truly linear system, as the tracking behavior does not show smooth oscillations but rather discrete positional adjustments (Figure 1). Thus this argument may mainly imply that the nonlinear system behaves in terms of its feedback delays as if it were simple and linear, with no phase lag caused by intrinsic dynamics.

Third, and perhaps most interesting, the period of primary peak depended on the task speed, changing by an average of 154 ms between the two target speeds tested. It is clear that this primary peak is a signature of the visual feedback control loop; and we know that the feedback loop delay is equal to half the oscillation period. This implies that the loop delay of the visuomotor feedback system changes by about 77 ms, from 341 ms for the slow task to

264 ms for the fast task. Thus I suggest that the predictive component responsible for negating the simple dynamic phase responses of the feedback loop may also affect the intrinsic processing time of the loop. If the tracking task is to move rapidly, the loop delay is effectively lower; if the task is to move more slowly, the loop delay is longer. I picture this as a form of "mental tuning" of the visual feedback loop, matching the system characteristics to suit the task at hand. It implies that the predictive element can cancel some of the loop processing delay, and this could be achieved by prediction of visual feedback on the basis of an internal model of the motor system. I have previously suggested that the cerebellum might form such a model (Miall, Weir, Wolpert, & Stein, 1993); if so, it would be interesting to test whether patients with cerebellar lesions show any evidence of this shift in feedback loop delay between fast and slow tracking tasks.

Are there other factors that could cause the change in delay? Clearly, reaction times are proportional to the difficulty of the task (Fitts & Posner, 1967; Georgopoulos, Kalaska, & Massey, 1981; Poulton, 1974), although it is also known that task difficulty rises with target speeds in an unpredictable tracking task (Pew, Duffendack, & Fensch, 1967b; Poulton, 1974). Thus, if the change in feedback delays were caused only by an increase in the subjects' reaction times, one would expect the reverse of what was observed. An alternative causal factor could be the error "deadzone" known to affect compensatory tracking (Wolpert et al., 1992). Subjects tend to correct their position after an error threshold has been crossed; thus in a slow task, in which subjects typically move in a clear step-and-hold fashion, it takes longer for the error to reach threshold, as the change in the error results mainly from target motion. At the target speeds used in this experiment, the deadzone would be expected to be about 0.15° for the slow task and 0.2° for the fast task (Wolpert et al., 1992). It can be shown that the minimum deadzone size required to account for a change of 77 ms in feedback-loop delay would be very much larger[3] and thus cannot account for the majority of the delay change.

I conclude that the time taken to use visual-feedback information is variable and is set according to the task being performed, presumably to maximize performance or minimize tracking effort. These results suggest that estimates of the visual processing delays made on the basis of tracking performance should not be extrapolated to other tasks.

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NOTES

1. This criterion is somewhat arbitrary. To my knowledge, however, no authors have suggested that the power band between 1–2 Hz represents separate frequency components. Instead, the consensus seems to be that the band represents the signature of visual guidance of the tracking movements (Miall et al., 1985; Neilson, Neilson, & O'Dwyer, 1988; Pew, 1974). It seems reasonable to restrict the analysis to a single component within this frequency band.

2. For example, a filter cut-off of 1.0 cycles per second (Hertz) applied to the frequency spectrum, treating the x-axis as time in seconds rather than frequency in Hertz.

3. The total feedback delay may be considered as an intrinsic delay ID plus the time T taken to reach the error deadzone, where, if DZ is the deadzone size and TV is the average target velocity, then $T = DZ/TV$. When the average target speed is doubled, $TV_2 = 2TV_1$. Given that $ID + (DZ_1/TV_1) = 341$ ms and $ID + (DZ_2/TV_2) = 264$ ms, then $DZ_1 - (DZ_2/2) = 0.077TV$. Because we know that DZ_2 is at least as large as DZ_1, then DZ_1 is a minimum of $0.154TV$. Because the target speeds used in these pseudorandom tasks ranged between 4 and 20°/s, DZ_1 would need to be between 0.6° and 3.1° to account for the time difference.

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