Intermittency in the Control of Continuous Force Production

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Received 13 July 1999; accepted in final form 16 May 2000

Slifkin, Andrew B., David E. Vaillancourt, and Karl M. Newell. Intermittency in the control of continuous force production. J Neurophysiol 84: 1708–1718, 2000. The purpose of the current investigation was to examine the influence of intermittency in visual information processes on intermittency in the control of continuous force production. Adult human participants were required to maintain force at, and minimize variability around, a force target over an extended duration (15 s), while the intermittency of on-line visual feedback presentation was varied across conditions. This was accomplished by varying the frequency of successive force-feedback deliveries presented on a video display. As a function of a 128-fold increase in feedback frequency (0.2 to 25.6 Hz), performance quality improved according to hyperbolic functions (e.g., force variability decayed), reaching asymptotic values near the 6.4-Hz feedback frequency level. Thus, the briefest interval over which visual information could be integrated and used to correct errors in motor output was approximately 150 ms. The observed reductions in force variability were correlated with parallel declines in spectral power at about 1 Hz in the frequency profile of force output. In contrast, power at higher frequencies in the force output spectrum were uncorrelated with increases in feedback frequency. Thus, there was a considerable lag between the generation of motor output corrections (1 Hz) and the processing of visual feedback information (6.4 Hz). To reconcile these differences in visual and motor processing times, we proposed a model where error information is accumulated by visual information processes at a maximum frequency of 6.4 per second, and the motor system generates a correction on the basis of the accumulated information at the end of each 1-s interval.

INTRODUCTION

A large body of evidence has been amassed demonstrating that vision supports achievement of a variety of goals of action, including transportation of the whole organism to a new destination, as in locomotion, and movement of an effector to a new position, as in reaching and aiming. In the latter category of action, at least, vision has been shown to serve the goals of movement according to the principles of closed-loop feedback control (e.g., Carlton 1992; Jeannerod 1991). A dominant characterization of this process is that, because of refractory periods and other delays in the system, visual feedback can only be used to modify motor output periodically or intermittently (e.g., Crossman and Goodeve 1983; Meyer et al. 1988; Vince 1948). The purpose of the current investigation is to characterize intermittency in the visual control of continuous force production.

The influence of visual information processes on movement control may express itself in motor output as changes in the form of movement trajectories (e.g., Doeringer and Hogan 1998; Miall et al. 1993a). In general, intermittency in movement control related to the processing of visual feedback has been evidenced by the appearance of “submovements” or discontinuities in movement trajectories, and their duration is thought to reflect the time necessary for the visuomotor system to sample current effector position against a target position and initiate a correction to the ongoing movement (Crossman and Goodeve 1983; Meyer et al. 1988). When vision is available during point-to-point movements of the hand (e.g., Carlton 1992; Elliott et al. 1997) and in the manual tracking of continuously varying waveforms (e.g., Miall et al. 1993a), submovements are reliably observed. However, when such movements are generated in the absence of vision, the number and submovements decline and there is a reduction in the accuracy of target approximation (e.g., Crossman and Goodeve 1983; Elliott et al. 1997; Miall et al. 1993a). These findings provide a basis for the inference that intermittencies in motor output (e.g., submovements, discontinuities) reflect the operation of intermittent, corrective visual feedback processes.

However, inferences about the visuomotor information and neural processes underlying the appearance of intermittencies in the control of limb position may be obscured by at least two mediating sources. These factors are minimized in continuous isometric control tasks where participants are required to maintain their force at target levels over extended durations: first, in isometric control, there is, by definition, no movement during force production; therefore, intervening biomechanical factors that may influence position control are minimized. On the other hand, during movement, there are complex shifts in the internal and external forces acting on the joint; stretch reflexes are elicited by changes in muscle length (Ghez and Gordon 1987; Taira et al. 1996; Ulrich and Wing 1993), and large portions of movement trajectory may unfold without correlated neural innervation of the musculature (e.g., McMahon 1984). Second, generating the appropriate output to meet the task demands of continuous force production seems at least logically less complicated than in the production of brief point-to-point (discrete) actions (Taira et al. 1996) or in the tracking of continuously varying waveforms. For instance, even in simple discrete actions (isotonic or isometric), the response needs to be initiated; it needs to meet the target requirement and then terminate (e.g., Gordon and Ghez 1987; Gottlieb et al. 1989). This sequence of

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events usually unfolds over a brief duration. While the tracking of continuously varying waveforms may minimize sudden movement initiation and termination, frequent reversals in position of the target and effector are common. Thus, in these tasks, evidence of closed-loop sensorimotor processes may be obscured or distorted by biomechanical factors and the presence of additional, ongoing information processes.

In the current study, we examine the control of continuous isometric force production when participants were instructed to maintain force at a target level [40% of the maximum voluntary contraction (MVC)] over an extended period (15 s) and to minimize force fluctuations around the target. To examine the relation between changes in the intermittency of visual information and intermittency in motor control, visual feedback about current force level was varied across conditions such that a feedback sample of the current force value in relation to the target was presented on a video monitor as infrequently as every 5 s to as frequently as approximately every 0.04 s (0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, 25.6 Hz). This manipulation should be informative about the capacity of the sensorimotor system to make use of the visual feedback information with which it is presented.

For this purpose, we assessed changes in force variability (within-subject standard deviation) and a measure of information transmission analogous to that used in the study of information transmission in physical (Shannon 1948) and biological systems (Fitts 1954; MacKenzie 1989; Slifkin and Newell 1999). Our measure of information transmission was the ratio of mean force output divided by the within-participant standard deviation (Doeringer and Hogan 1998; Slifkin and Newell 1999). An expectation is that increases in the amount of visual information would result in decreases in the within-participant standard deviation and increases in information transmission, although the exact form of these relations has yet to be established.

A linear regression equation with a y-intercept of zero and a slope specifying a 1:1 ratio between incoming visual information and information transmitted to motor output would characterize a perfect information transmission system. However, it is well documented that although the visual system by itself can pick up information at relatively high rates (~60 Hz; e.g., Gregory 1997), there are limits on the speed with which feedback information can be utilized in the service of correcting errors in motor control (e.g., Carlton 1992). Therefore, it was anticipated that performance would improve up to a point with increases in visual information, and slow or cease improving with further increases in the frequency of visual feedback information. In this case, the relation between increases in the frequency of visual information and information transmitted to motor output should be specified by a hyperbolic increase or negatively accelerating function. Alternatively, a hyperbolic decay or negatively decelerating function would be the predicted relation between feedback frequency and the within-subject standard deviation. In the case of either a hyperbolic increase or decay, a slowing or a stop on improvement in performance quality should point to limitations of the speed with which visual information can be used to implement corrections in motor output.

We also examined the frequency content of force output, using the power spectrum, to identify the frequencies of force output intermittencies related to closed-loop visuo-motor control. According to previous research, the frequencies in the power spectrum of motor output associated with closed-loop sensorimotor control are located in the 1–2 Hz frequency band (e.g., Freund and Hefter 1993; Kunesch et al. 1989; Miall 1996; Miall et al. 1993a). In this case, one hypothesis is that the feedback frequency manipulation should exclusively influence changes in power in this range, while the power at other frequencies does not change. In particular, if increases in feedback frequency result in reductions in force variability, then it is anticipated that those reductions would exclusively be mediated by reductions in the amount of spectral power in the 1–2 Hz frequency range. An alternative hypothesis would be that participants generate a corrective motor response to each feedback delivery. In this case, increases in feedback frequency might appear to couple or entrain increases in the frequency of oscillations in force output. This should be reflected by a positive correlation between feedback frequency and shifts of power to higher frequencies.

In summary, the current experiment was designed to precisely manipulate a range of visual feedback intermittencies (feedback frequencies) and examine their influence on intermittency in continuous isometric force control. Two issues were addressed in the current experiment. First, we wanted to identify the capacity of the motor system to make use of the available visual information through examining the effect of the scaling of the frequency of visual feedback information on changes in the quality of performance outcome. Second, we sought to identify the spectral frequencies of force output related to the processing of visual feedback information (Freund and Hefter 1993; Miall 1996). The hypothesis examined was that changes in visual feedback should exclusively influence motor output intermittencies with frequencies in the 1–2 Hz band of the power spectrum.

**Methods**

**Participants**

Ten individuals, with a mean age of 25.4 yr (SD = 4.43), from The Pennsylvania State University community participated as volunteers in the experiment. Four of the participants were female, and none of the 10 participants had a prior history of a neurological disorder. Participants performed the task with the index finger of their dominant hand: six were right- and four were left-hand dominant. Eight of the participants were unfamiliar with the task and the purpose of the experiment, and the remaining participants were the first (A.S.) and second (D.V.) authors of the current paper. The eight naive participants provided informed consent, which was approved by the local institutional review board.

**Apparatus**

Much of the apparatus, procedures, and data analyses used in the current protocol have previously been described (Slifkin and Newell 1999). Seated participants produced force by pressing on a load cell with the pad of their distal interphalangeal segment of the index finger. During an experimental trial, force output from the load cell was amplified and then sampled at 100 Hz by a 16-bit A/D board that measured force in units of 0.0015 N (0.147 g).

The load cell was located 40 cm in front of the participant’s body midline and fixed to a desktop. Although no physical restraint was used, participants were instructed to keep their elbow, forearm, and all fingers flat against the surface of the desktop and to limit force production to index finger flexion. Participants were reminded of these...
instructions during the experiment. A 14-in. computer monitor was placed on a separate tabletop so that it was located at a distance of 75 cm from the center of participants’ eyes. Participants viewed their force output on the computer monitor. It had a viewing area composed of 459 vertical pixels by 638 horizontal pixels. The dot pitch (the width of the dots that make up each pixel) was 0.028 cm. We set the display-to-control gain at 50 pixels/N, and this resulted in an excursion of the force-time trajectory on the video monitor over a distance of 50 pixels for a change in force of 1 N.

During each trial, participants adjusted their force output to a force target that appeared as a horizontal line (1 pixel in width) spanning the length of the video monitor. The force target represented 40% of the MVC and was always vertically centered on the video monitor. Thus, the target line divided the video display such that half of the 459 pixels comprising the vertical dimension of the display appeared above the target line (+229 pixels), and half below the target line (−229 pixels). Given that the display-to-control gain was set at 50 pixels/N, the force-time trajectory could deviate by as much as 4.59 N above and 4.59 N below the target and still remain in view on the video monitor. For example, if the 40% MVC level for a participant was 15 N, then the force-time trajectory remained visible when it remained between 10.41 and 19.59 N. On the basis of prior data (e.g., Slifkin and Newell 1999), this range of permissible variability around the target was in far excess of the levels of variability participants exhibit at a 40% MVC force requirement. It was only during the very start of the trial when participants adjusted their force to the target level that the force-time trajectory was not in view. Although we recorded the full 15-s force-times series, we were only interested in, and only examined force output after, this initial period of adjustment. All participants during all trials quickly increased their force to levels near the requirement and maintained their force within the visible range.

Procedures

During the initial portion of the experiment, the participant’s MVC was assessed (see Methods of Slifkin and Newell 1999). During both the familiarization and the experimental trials, the force requirement for each participant was based on 40% of their MVC. There were eight feedback frequency levels imposed, and feedback frequency was defined as the number of pixels lit per second. The feedback frequency levels used here were 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, and 25.6 Hz.

The left column of Fig. 1 is a representation of some aspects of the image viewed by the participant on the computer monitor at the end of the trial. As seen from top to bottom on the left side of Fig. 1, as the feedback frequency increased, both the time interval and distance between the appearance of consecutive pairs of illuminated pixels decreased. For example, at 0.2 Hz, there was a horizontal spatial interval of 5.95 cm between consecutive feedback samples and a temporal interval of 5000 ms. At 0.8 Hz, the spatial and temporal intervals were quartered to 1.49 cm and 1,250 ms, respectively.

From trial onset, the first feedback sample was displayed when the time interval associated with the active feedback frequency interval elapsed. Then, as each subsequent fixed time interval elapsed, feedback samples (illuminated pixels) were displaced, at the specified distance and time, from the left of the previous feedback presentation. This process iterated until the end of the 15-s trial and resulted in the compilation of a sequence of illuminated pixels on the display as time elapsed into the trial. Once displayed, each feedback sample remained illuminated until the end of each 15-s trial when the display was cleared in preparation for the next trial. For example, in the 0.2-Hz condition, the first feedback sample was presented at 5 s into the trial; the second feedback sample was presented at 10 s into the trial, and the third feedback sample was presented at 15 s into the trial. With a spatial interval of 5.95 cm between feedback samples in the 0.2-Hz condition, the first feedback sample appeared at a horizontal distance of 5.95 cm, the second at 11.90 cm, and the third at 17.85 cm from the left edge of the feedback display.

FIG. 1. Examples of feedback display and force-time series for force produced under different conditions of feedback frequency: 0.2, 0.8, 3.2, and 12.8 Hz. All four examples come from the same participant’s performance at the initial trial of the depicted feedback frequency level. The left column provides a depiction of the appearance of the video display (not to scale) once a 15-s trial elapsed. In the right column is the corresponding force-time trajectories sampled at 100 Hz. The horizontal line in each panel represents the force target of 40% of the maximum voluntary contraction (%MVC), and, as shown in the left column, was presented at the center of the video display throughout the trial. Both the mean force (M) produced and the standard deviation (SD) are presented for each force-time series. As in all data analyses in this experiment, the M and SD values were based on the 4th through 10th s of the 15-s time series. This period is marked by the vertical dotted lines in the right column. Force was measured in Newtons (N).
Data analysis

GENERAL DATA PROCESSING. The first 4 s and last 1 s of each force-time series were omitted from all analyses. The initial 4 s was omitted in order to ensure that the time series did not include the period over which force was being adjusted and stabilized, and the final 1 s was omitted, as on some occasions, some participants released their finger from the load cell during the final moments of the trial. Aside from the calculation of the mean force output, a linear regression equation was fit to each time series and the residuals from the line of best fit were used for additional data analysis. This procedure removed any trend (nonzero slope) from the time series. Although the presence of such trends was negligible, we used this detrending procedure as it is known that time series analyses can be biased by nonstationarities in a signal. Following detrending, each time series was conditioned with a ninth-order Butterworth filter having a 30-Hz low-pass cutoff.

MEASURES OF PERFORMANCE OUTCOME QUALITY. The descriptive statistics submitted to analyses were the mean force, the standard deviation, and a measure of information transfer (mean force/standard deviation of force). Analyses of mean force output and the within-subject standard deviation provided an opportunity to assess how changes in feedback frequency influenced participant’s ability to, respectively, adjust their force to the force requirement and minimize force variability as feedback frequency increased. The measure of information transmission used here can be seen as analogous to informational measures adopted for use in the study of motor control. Such indices have been based on logarithms of ratios of movement amplitude requirements divided by the region of permissible endpoint variability [viz., Fitts 1954: \( \log_2 (2A/W) \)], or the actual (effective) average response amplitude divided by the actual variability of response endpoints (e.g., Welford 1968).

THE STRUCTURE OF FORCE OUTPUT. In addition to analyses aimed at addressing the main issues, we also provide an assessment of the influence of intermittencies in visual feedback on intermittencies in the global dynamics of continuous force output. This was accomplished in two ways: approximate entropy was used as an index of force output dynamics in the time domain (see Pincus 1991; Pincus and Goldberger 1994), and spectral analysis was used to evaluate the profile of the frequency domain (e.g., Lipsitz 1995).

Approximate entropy returns a single value reflecting the predictability of future values in a time series on the basis of previous values (Pincus 1991; Pincus and Goldberger 1994). As signal structure changes from, for example, a sine wave, where there are accurate short- and long-term predictions of future values in a time series, to a randomly generated signal (viz., white Gaussian noise), where each value in the time series is generated independently of the other time series values, approximate entropy increases to a maximum near a value of 2. Thus increases in the approximate entropy value of a signal are said to reflect increased noisiness or complexity in its time domain structure. Detailed descriptions of the multi-step algorithm used in the calculation of approximate entropy are available in other sources (see Pincus 1991; Pincus and Goldberger 1994; see Appendix of Sliškin and Newell 1999). The same algorithm and parameter settings were used here and in our prior work (Sliškin and Newell 1999).

The power spectrum was computed using the SPECTRUM command in MatLab v. 4.2 (MatLab 1994) and it uses Welch’s averaged periodogram method. Each time series was divided into sections of 256 data points through a Hamming window and then submitted to a spectral analysis. The individual spectra were averaged to provide the resultant spectrum for each trial. The power spectrum of each trial was divided into 40 bins of 0.39 Hz which provided a frequency range of 0 to 15.63 Hz. The power in each frequency bin represented the portion of total power in the overall amplitude of force output oscillations that could be attributed to the frequencies specified by that bin. Changes in the distribution of power over the frequency range, as a function of feedback frequency, were indexed by fitting a power function to the spectral profile

\[
P = af^b \tag{1}
\]

In this equation, the power function exponent, \( b \), is a parameter that scales changes in spectral frequency, \( f \), to changes in spectral power, \( P \). When changes in power as a function of frequency are viewed graphically, \( b \) identifies the slope (e.g., see Gescheider 1997) or rate of change of spectral power as a function of frequency within a spectral profile (e.g., Gilden et al. 1995; Lipsitz 1995), while \( a \) represents the \( y \)-intercept of the equation (e.g., see Gescheider 1997), or, in other words, the location where the function crosses the \( y \)-axis on the graph. For the purposes of the current study, only the value of \( b \) was of interest. As the power spectrum becomes more broadband, and therefore closer to white Gaussian noise, the value of the power function exponent increases from negative values toward zero. Thus, like approximate entropy, the exponent of the power spectrum provides another means of obtaining a global description of the structure of force output.

For each of the dependent variables described so far, measures extracted from each trial were placed in a two-way feedback frequency (8) \( \times \) trials (4) analysis of variance (ANOVA). Among all of the computed ANOVAs, there was only a single trials effect and no interactions of feedback frequency with trials. Furthermore, because changes in the dependent variables as a function of trials were not of interest to our current purposes, only feedback frequency effects are reported here. For all analyses in this paper, when results are identified as significant, there was less than a 5% chance of a Type I error (\( P < 0.05 \)). When relevant, Tukey’s honestly significant difference (HSD) test was used to identify the locus of an effect found in the ANOVA.

TREND AND BREAKPOINT ANALYSES. The ANOVAs enable a test of the null hypothesis that visual feedback should not influence continuous isometric force production. Given an effect, it was then of interest to specify the form of the relation between changes in visual feedback information and the dependent variables considered here. This would provide information about the capacity of the system to use visual information in the modulation of force output. Accordingly, the trend and breakpoint analyses provided, respectively, an opportunity to identify possible constraints on the use of visual information and the level of feedback frequency where the limitation occurs.

Changes in the dependent variables as a function of feedback frequency were characterized by three parameter hyperbolic regression equations specifying increases (Eq. 2), or decreases (Eq. 3), depending on the direction of change in the dependent variable

\[
y = y_0 + (ax)/(b + x) \tag{2}
\]

\[
y = y_0 + (ab)/(b + x) \tag{3}
\]

These equations were used both to describe changes in the group mean data and changes in the individual-participant trends as a function of feedback frequency level. In the individual-participant case, the data points fit by the equation were based on means across the four trials at each feedback frequency level.

The line of best fit from the hyperbolic regression was then used to identify the feedback frequency level at which the dependent variable stopped changing. This breakpoint in the function was taken as an estimate of the shortest feedback interval over which visual information could be used to influence changes in the dependent variable under consideration. Each line of best fit consisted of 257 consecutive trials at each feedback frequency level.

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In this procedure, the second derivative of each value in the loss function associated with the best-fitting hyperbolic regression was calculated. This is informative about how fast the slope of the function changes at each successive value. The breakpoint in the function was identified as the predicted feedback frequency level where the second derivative value of the loss function first fell below 0.0001 (the convergence criterion). The feedback frequency at this breakpoint then became our index of the fastest frequency (the shortest interval: the minimum visual processing time) at which visual feedback information could be integrated and used to improve performance quality. See Fletcher (1969) for more details on the quasi-Newton estimation procedure.

FREQUENCY ANALYSES. In an attempt to provide a more detailed examination of the feedback frequency manipulation than could be provided by the more global indices of the structure of force output (approximate entropy, the power spectrum exponents), we examined changes across the feedback frequency level at successive bin widths of 1.95 Hz over a range from 0 to 15.63 Hz. This provided eight consecutive frequency bins. For each trial within a feedback frequency level and for each participant, the power across the five smaller 0.39-Hz bins within the 1.95-Hz range was averaged. The average power in each 1.95-Hz bin was again averaged across the four trials at the respective feedback frequency level. The eight resultant values for each participant were then entered into a two-way feedback frequency (8) by spectral bin (8) ANOVA. One-way ANOVAs were subsequently used to examine changes in average power as a function of feedback frequency level, at each spectral frequency bin. This analysis was aimed at determining which frequencies in the spectrum were influenced by the visual feedback manipulation.

RESULTS

Performance outcome quality

The across participant average MVC was 31.44 N (SD = 11.11 N) so that the 40% MVC force requirement was on average 12.58 N. Figure 1, right column, provides illustrations of the force-time trajectories sampled and stored at 100 Hz. These images, from a randomly selected participant, were taken from the first trial at each of the displayed feedback frequency levels. It can be observed that with increases in feedback frequency (from top to bottom, right column) came improved approximation of the target level (40% MVC) and declines in the magnitude of variations around the target force values. The decline in variability also appeared to be related to reductions in the contribution of lower frequency oscillations to the signal. What is clear from this illustration is that increasing the temporal resolution of force-feedback results in performance enhancement.

As seen in the top left of Fig. 2, group averages for mean force output increased sharply, although only slightly, in an absolute sense or in terms of %MVC: mean force increased from about 12 N at 0.2 Hz to 12.4 N at 1.6 Hz, across the first five feedback frequency levels, and this translated into just less than a 1.5% MVC increase in force. Then, with increases in feedback frequency, mean force output appears to remain stable from the 1.6 to 25.6 Hz feedback frequency levels, where mean force output remained at levels just below (about 0.18 N or 0.5% MVC) the force target. The increases in mean level of force output were significant over the feedback frequency range, \(F(7, 63) = 6.01, P < 0.001\), but the Tukey HSD test revealed that this effect was carried by the mean force under the lowest feedback frequency level (0.2 Hz) falling below the means of all other feedback frequency levels. Thus, even though participants did not deviate very far below the force requirement over the 128-fold change in feedback frequency (from 0.2 to 25.6 Hz), and the significance of the ANOVA was carried by differences only at the 0.2-Hz feedback frequency level, it may be concluded that increases in feedback frequency did enhance participant’s ability to approximate the target.

As seen in the top right of Fig. 2, the standard deviation declines in a negatively decelerating fashion from about 0.9 N at 0.2 Hz to about 0.3 N at 6.4 Hz and then essentially
stabilizes thereafter. This large (~66%) decline in the standard deviation as a function of feedback frequency was highly reliable, \( F(7, 63) = 24.23, P < 0.001 \). Figure 3 provides an illustration of changes in the standard deviation as a function of feedback frequency for each of the 10 individual participants. In very good agreement with the group mean trends, it can be seen that all individuals show a sharp decrease in the standard deviation over the initial levels of feedback frequency and then little, if any, change thereafter. The point at which the standard deviation appears to stop changing, or substantially slows its change, appears to occur near the 3.2- or 6.4-Hz feedback frequency level in all individuals.

As seen in the middle of Fig. 2, expressing the disproportionate reductions in the standard deviation relative to the mean force output, information transfer (M/SD) sharply increased from the initial intermittency level until the 6.4-Hz level and then continued to increase, but at a slower rate over the remaining levels of the variable. There was a threefold, highly significant, \( F(7, 63) = 37.74, P < 0.001 \), increase in information transfer over the feedback frequency range. Thus, there was neither a 1:1 relation between the frequency of visual information and information transferred to motor output, nor the relation linear: there was nearly a fourfold increase in information transfer across the first six increments (0.2 to 6.4 Hz), but only about a 0.3:1 increase across the final three increments (6.4 to 25.8 Hz).

The structure of force output

In parallel with the measure of information, and varying inversely with the standard deviation, Fig. 2, bottom left, shows that approximate entropy increases according to a hyperbolic or negatively accelerating trend. Thus, noisiness in the intermittencies of force output increased over the initial levels, but substantially ceased increasing following the 6.4-Hz feedback frequency level. These changes over the range of feedback frequency values were highly significant, \( F(7, 63) = 44.87, P < 0.001 \).

As illustrated in Fig. 3, it can be seen that in agreement with the group mean trend (Fig. 2), all individuals show sharp increases in approximate entropy over the initial levels of feedback frequency and then little, if any, change thereafter. A comparison between the group mean trends for the standard deviation (Fig. 2, top right) and approximate entropy (Fig. 2, bottom left), as well as their individual trends (Fig. 3), reveals that reductions in force variability were related to increased complexity or noisiness in the intermittencies of force output.

Figure 2, bottom right, shows that the power function exponents taken from the power spectrum changed in a parallel fashion with information and approximate entropy and were inversely related to changes in the standard deviation: the power function exponents became increasingly less negative from the first to fourth increment in feedback frequency. There was a more gradual increase toward zero across the next three increments. Overall, these changes gave rise to a significant effect for feedback frequency, \( F(7, 63) = 10.11, P < 0.001 \). Thus, the processing of increasing amounts of visual information was related to a broadened distribution of spectral power that can be said to reflect increased noisiness in the frequency domain of continuous force output.

Trend and breakpoint analyses

As can be seen by viewing the group mean data in the panels of Fig. 2, the hyperbolic regression equations provided very good descriptions of changes in each dependent variable as a function of feedback frequency. The proportion of variance accounted for (\( r^2 \)) by the hyperbolic regression equations fit to the group mean trends and averages based on \( r^2 \) values from each of the 10 individual trends were, respectively, 0.88 and 0.61 (SD = 0.39) for mean force output, 0.98 and 0.88 (SD = 0.09) for the within-participant standard deviation, 0.99 and 0.90 (SD = 0.05) for information transfer, 0.98 and 0.89 (SD = 0.08) for approximate entropy, and 0.93 and 0.52 (SD = 0.36) for the power spectrum exponents. Thus, for the standard deviation, information, and approximate entropy there was only about a 10% decrease in the averaged-individual \( r^2 \) values from that of the corresponding group mean values. Indeed, a comparison of the individual participant trends for the standard deviation and approximate entropy (Fig. 3) to their group mean trends indicates that the form of the individual trends have a very good correspondence with their respective group mean trends. On the other hand, for mean force and the power spectrum exponents, there were about 30 and 40% decreases, respectively, in the averaged-individual \( r^2 \) values from that of their group mean trends.

The feedback frequency associated with the point in the hyperbolic function where it stopped changing (the breakpoint) was taken as the estimate of the minimum visual processing time, or, in other words, the shortest time interval over which visual information could be integrated and used to improve the quality of performance outcome or affect a change in the dynamics of force output. The breakpoints are reported here in terms of their associated feedback frequency (Hz) level, and, parenthetically, are translated into their corresponding time intervals (ms). The breakpoints for the group mean and averages based on the 10 individual functions were, respectively, 5.06 Hz (198 ms) and 5.91 Hz [169 ms (SD = 55 ms)] for mean force output, 6.55 Hz (153 ms) and 6.26 Hz [160 ms (SD = 35 ms)] for the standard deviation, 8.04 Hz (124 ms) and 7.94 [126 ms (SD = 15 ms)] for information transfer, 6.95 Hz (144 ms) and 7.13 Hz [140 ms (SD = 22 ms)] for approximate entropy, and 10.62 Hz (94 ms) and 6.43 [156 ms (SD = 36 ms)] for the power spectrum exponents.

Of the variables considered, the mismatch between the minimum visual processing times based on the hyperbolic trends fit to the group mean data and averages of the individual minimum visual processing times was greatest for the power spectrum exponents and then the mean force. Visual inspection of the individual-participant trends for these dependent variables revealed that this lack of correspondence was related to a lack of between-participant consistency in the form of the individual hyperbolic trends and, as just reviewed, the quality of the hyperbolic function fit. Alternatively, there were very small differences between the group mean and averaged-individual breakpoints for the standard deviation, information, and approximate entropy, and this points to high levels of consistency in the form of the individual-participant functions and the quality of their fit. Nevertheless, in general, taken together, the identified processing times fell within a narrow range that is similar to the range of estimates identified in studies on discrete
FIG. 3. Changes in the within-participant standard deviation and approximate entropy as a function of feedback frequency for each of the 10 participants in the study. Each data point represents an average over the four trials performed at each feedback frequency level. The within-participant standard deviation was measured in Newtons (N) and approximate entropy was measured on a unitless scale ranging from 0 to about 2. The line of best fit was derived from a hyperbolic equation specifying a decaying (Eq. 3) and increasing function (Eq. 2), respectively, for the within-participant standard deviation and approximate entropy. For each participant, the trends for both variables are plotted on the same set of axes with the left abscissa corresponding to values of the standard deviation and the right abscissa corresponding to approximate entropy. The two character label (PX) in each panel was assigned on the basis of the order in which the participant was run in the experiment. Participants 2 (P2) and 10 (P10) were, respectively, the second (D.V.) and first (A.S.) authors of the current experiment.
Frequency analyses

The exponents from power functions fit to the power spectrum provided a global index of changes in the distribution of spectral power as a function of changes in the amount of visual information. To gain a more fine-grained view of how changes in the amount of visual information influenced the frequency content in specific regions of the power spectrum, the spectrum was subdivided into eight bins with widths of 1.95 Hz. The independent and dependent variable values in both panels of Fig. 4 were submitted to a logarithmic (base 10) transformation. This was done to provide an enhanced view of aspects of the data presentation that would otherwise be masked when viewed in untransformed coordinates. Namely, this procedure provided a clearer image of the form of the functions describing changes in spectral power with feedback frequency, at the spectral frequency bins greater than 1.95 Hz (Fig. 4, top). All statistical analyses of power spectra reported here were based on the untransformed data. However, the same main effects and interactions were found when the ANOVA was applied to either the transformed or untransformed data.

Figure 4, top, shows that the average power in the 0–1.95 Hz bin was elevated above that seen at the higher spectral frequencies, but was systematically reduced with increases in feedback frequency level. However, unlike the declines in power seen in the 0–1.95 Hz spectral bin, it appears (Fig. 4, top) that changes in average power over feedback frequency are absent in the higher frequency bands of the power spectrum. Therefore, the decrease in power in the 0–1.95 Hz band would seem to be responsible for both a significant feedback frequency effect, $F(7, 63) = 4.48, P < 0.001$, as well as a feedback frequency by spectral bins interaction, $F(49, 441) = 4.60, P < 0.001$, in the two-way feedback frequency by spectral bins ANOVA. This observation was confirmed by one-way ANOVAs used to examine changes in power over feedback frequency levels, at each spectral frequency bin: significant declines in power were observed only in the 0–1.95 Hz, $F(7, 63) = 2.52, P < 0.05$, but not at higher spectral bins.

When viewed in linear coordinates, decreases in power in the 0–1.95 Hz spectral frequency bin appear to follow a hyperbolic decay similar to that seen for the standard deviation (Fig. 2, top right), with power ceasing to change beyond the 6.4-Hz (~150 ms) feedback frequency level. In support of this observation, there was a high correlation, $r(6) = 0.94, P < 0.01$, between the group means for the standard deviation and average power in the 0–1.95 Hz spectral bin. Taken together, the results indicate that reductions in the standard deviation, an index of the amplitude of force variability, were mediated by reductions of power only in the 0–1.95 Hz bin.

As seen in Fig. 4, top, the average power at each feedback frequency level in the 0–1.95 Hz spectral bin was elevated above the corresponding group means in all other spectral bins. Then, as the spectral frequency bin increased, there were systematic declines in average power. Indeed, the two-way ANOVA revealed that there was a significant main effect for spectral bin, $F(7, 63) = 10.12, P < 0.001$. However, the Tukey HSD post hoc test showed that this resulted from the average power in the 0–1.95 Hz bin being significantly elevated over the power in every other spectral frequency bin: no differences in power were found among the seven higher spectral frequency bins.

Figure 4, bottom, shows changes in power as a function of spectral frequency bins, in five 0.39-Hz increments, at each of the eight feedback frequency levels. This analysis provided a more detailed image of the power spectrum in the region where changes in spectral power were found (0–1.95 Hz). It can be seen that as a function of spectral frequency bin, power increases from the initial bin with an upper limit of 0.39 Hz and reaches maximum levels at bins with upper limits of 0.78 and 1.17 Hz, and declines thereafter. This inverted U shape was preserved for the spectra at each feedback frequency level and resulted in a significant spectral bins effect, $F(4, 36) = 6.67, P < 0.001$, in the two-way frequency by feedback frequency (8) by spectral bins (5) ANOVA. A reliable feedback frequency effect, $F(7, 63) = 4.59, P < 0.001$, reflects the trend for power to decrease as feedback frequency increased. A feedback frequency by spectral bins interaction was present, $F(28, 252) = 3.45, P < 0.001$, and resulted from differences in the degree of change in spectral power as a function of feedback frequency, at the different spectral frequency bins. For example, in the spectral...
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was possible to address several theoretical issues regarding the intermittency of visual feedback was parametrically varied, it of continuous force output. Using this paradigm in which the influence of intermittency in visual information on the control process are restricted to a distinct, low-frequency bandwidth of motor output (Freund and Hefter 1993).

DISCUSSION

The experiment presented a novel means for examining the influence of intermittency in visual information on the control of continuous force output. Using this paradigm in which the intermittency of visual feedback was parametrically varied, it was possible to address several theoretical issues regarding the influence of variations of the intermittency of visual information on intermittency in force output.

Visual feedback intermittency and performance outcome

Increases in the frequency of visual feedback had a strong impact on the quality of performance outcome and the dynamics of continuous force production. Given this result, it was of interest to determine the nature of these relations. Were there linear and proportional changes in the characteristics of motor output accompanying increases in visual information? Such a result would indicate that the motor system could continuously access and utilize all incoming visual information to meet the goals of matching force to, and minimizing fluctuations around, the force requirement. However, changes in dependent variables as a function of feedback frequency departed greatly from a linear regression equation with a slope specifying 1:1 relations between the independent and dependent variables. In fact, in confirmation of the prediction (see INTRODUCTION), changes in dependent variables were best described by hyperbolic increases or decreases, changing sharply over the initial force requirements and remaining at asymptotic levels over the final few feedback frequency levels. The slowing and then asymptote of these functions suggest that the feedback frequency levels used here were sufficient to assess performance over the range which participants have sensitivity to the manipulation, and, moreover, we were able to capture the upper limit at which the visuomotor system can effectively use the intermittency of visual feedback information delivered.

Visualmotor processing times

VISUAL FEEDBACK PROCESSING TIMES. According to the break-

point analysis, participants were unable to further improve their compliance with the instruction to minimize force vari-

ability (the standard deviation) when the interval between successive feedback deliveries was shorter than about 150 ms (6.4 Hz feedback frequency). Changes in the dynamics of force output, as indexed by approximate entropy, continued until slightly faster frequencies, while changes in information transmission persisted over even shorter intervals. The ordering of the breakpoint values for the different variables suggests that different dimensions of motor output have different capacities of influence by visual information. Nevertheless, these between-variable differences in breakpoint estimates were quite small.

While it is clear that changes in the dependent variables as a function of feedback frequency were well described by hyperbolic equations, there was a tendency for the group mean functions to change slightly over the final feedback frequency levels. However, this would seem to come as a result of averaging across the individual data. An examination of the individual participant trends for the standard deviation and approximate entropy (Fig. 3) revealed that, in comparison with the group mean trends, the functions stop changing more abruptly and remained stable over the final feedback frequency levels.

MOTOR OUTPUT PROCESSING TIME. Improvements in perfor-
mance outcome accompanying increases in feedback frequency were related to reductions in the amplitude of power at low frequencies (0–1.95 Hz), with no changes in power across the higher frequency bands. Decreases in power in the 0–1.95 Hz frequency bandwidth over the range of feedback frequencies could best be described, when viewed in linear coordinates, according to a hyperbolic decline that paralleled decreases in the variability of force output. Thus, visual information facilitated compliance with the instruction to minimize variability through a mechanism that operates exclusively on reductions in low-frequency fluctuations of force output. When we examined the power spectrum in the 0–1.95 Hz region more closely, it was found that power was peaked at either the spectral bins with upper limits of 0.78 Hz and 1.17 Hz, which were reliable at all

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tracking of continuously varying waveforms (e.g., Miall 1996; Miall et al. 1993a). For instance, in a delayed feedback paradigm, when the interval between movement and the appearance of displayed visual feedback was varied, there were correlated shifts in power within low frequencies in the spectrum, but power at higher frequencies was left unaffected (Miall 1996). In addition, according to a model proposed by Freund and Hefter (1993), power located between 1 and 2 Hz in motor output power spectra is generally related to movements requiring on-line sensory guidance or movements generated in the service of the acquisition of sensory information (Kunesch et al. 1989). On the other hand, movements generated at slightly higher frequencies are related to the quickest possible voluntary movements and those at even higher frequencies are related to involuntary output attributed to physiological tremor and the mechanical resonance of the involved effector system. Thus, the current results are consonant with the hypothesis that expressions of sensorimotor control processes are confined to a distinct range of low frequencies in the spectrum of motor output oscillations (e.g., Freund and Hefter 1993; Kunesch et al. 1989; Miall 1996).

Infering processing times. Two techniques have been used to infer inferences about the speed of the visuomotor feedback loop. One method is based on the use of data analytic techniques that examine the dynamics of movement trajectories to assess markers of the cycle time of feedback-based corrections. This includes assessing submovement durations (e.g., Carlton 1992; Crossman and Goodeve 1983; Meyer et al. 1988) or looking for shifts in the peak frequency of the power spectrum as a function of a visual feedback manipulation (e.g., Miall 1996). Indirect methods are experimental techniques that involve changing the duration of exposure to visual feedback during movement and then examining resultant changes in movement accuracy (e.g., Keele and Posner 1968). For example, the minimum interval needed to process visual information has been inferred through identification of the shortest duration exposure to on-line visual feedback information where performance quality (e.g., deviations from the movement target) is improved over a condition where no vision was available (e.g., Keele and Posner 1968; Vince 1948; Woodworth 1899).

In the current study, we have examined performance using both direct and indirect methods, the power spectrum, and estimates of limits on improvement in performance outcome quality as a function of feedback frequency (breakpoint analysis), respectively. However, the processing time estimates from the two methods do not correspond. The peak in the power spectrum remains stationary at around 1 Hz, and estimates using the breakpoint analysis yield values of 6.4 Hz corresponding to a time interval of 150 ms (Fig. 3, middle).

One way to reconcile these differences is to consider that the two estimates represent two processes that act together toward the achievement of adaptive visuomotor control. According to one account, the motor system implements motor output corrections at a rate of one each second (1 Hz). During the period between corrections, superimposed processes of visual perception sample the displayed feedback and assess force output errors (force target-force feedback differences) at a maximum rate of 6.4 feedback samples within a 1-s period. Each successive error is then accumulated in short-term storage. Then, as the 1-s interval between the collection of feedback samples nears its end, an error correction signal is computed, the magnitude of which is scaled to the size of the accumulated error information. The feedback loop is closed when a correction to force output is implemented at the end of the 1-s period between corrections. This is one possible account of the visuomotor control process in this task, but other versions may be considered (e.g., Miall et al. 1993b). Nevertheless, the parsing of visual (~150 ms) and motor (~1 s) processing times identified here match the respective times identified in empirical studies on the tracking of continuous waveforms (Miall et al. 1985) and those used as parameter values in quantitative models of tracking behavior (Miall et al. 1993b).

Visual feedback information and force output noisiness

As a result of the reductions in power as a function of feedback frequency in the 0–1.95 Hz frequency band (Fig. 4, top), power became more equally distributed (broadband) across the range of force output frequencies considered. Thus, intermittencies in force output become closer in structure to white Gaussian noise. However, this occurs not because of a spread of power to higher frequencies, but rather because of a reduction of power in the 0–1.95 Hz frequency band, with power at higher frequencies remaining constant. Revealing changes in the time domain structure of continuous force output, the group means for approximate entropy increased hyperbolically, indicating that intermittency in force output tends toward increased complexity or noisiness with increases in visual feedback information.

Very high correlations were found between measures of performance outcome quality and measures of force output noisiness, both when the group means and the individual data were considered. For example, as force variability declined (the standard deviation) as a function of increases in feedback frequency, there were parallel increases in approximate entropy. The correlation of the group mean data for the standard deviation (Fig. 2, top right) and approximate entropy (Fig. 2, bottom left) was $r = -0.99$, and an average of the 10 individual participant correlation coefficients for this relation was $r = -0.94$ (Fig. 3). The same relationship, in terms of increases in the noisiness in the intermittencies of force output and increases in the quality of performance outcome, was also found when performance was modulated, not by varying the amount of available visual information, but rather by challenging the force production capacity of the motor system (Slifkin and Newell 1999). Thus, the findings of the current study provide additional support for the notion that, in contrast to prevailing information processing accounts of human performance (e.g., Meyer et al. 1988; Schmidt et al. 1979), increases in the noisiness of force output were related to enhancement, and not decrement, in the quality of performance outcome.

Conclusion

The current study has provided an examination of the influence of variations of the intermittency of visual feedback on intermittencies in continuous force production. We found, first, that increases in the amount of visual information resulted in highly reliable improvements in performance that continued until about the 6.4-Hz feedback frequency level, yielding a minimum visual processing time of 150 ms. Second, these
improvements in performance across feedback frequency were mediated exclusively by correlated reductions of power at about 1 Hz in the power spectrum, without changes at higher spectral frequencies. Support was not found for a hypothesis that increases in feedback frequency should entrain correlated shifts in power to higher frequencies in force output: the stability of the modal spectral frequency over the 128-fold increase in feedback frequency is consistent with findings in other domains showing that sensorimotor control operates only at low frequencies in motor output power spectra (e.g., Freund and Hefter 1993; Miall 1996). To reconcile the differences between visual (6.4 Hz) and motor (1 Hz) processing times, we proposed a model where error information is accumulated by the visual system at a maximum frequency of about 6.4 per second, and the motor system generates a correction on the basis of that information at the end of each 1-s interval. An additional observation, through global analyses of the dynamics of force output (power spectrum exponents, approximate entropy), revealed that as feedback frequency increased there was an increase in the noisiness of the intermittencies in force output structure. In turn, these increases in signal noisiness were related to improvement in the quality of performance outcome. This finding extends previous work where the same relation between information transmission and signal noisiness was found (Slifkin and Newell 1999), but the relation was mediated by maintenance of continuous isometric force output at different force levels and not variations of visual feedback information.

This research was supported in part by National Institutes of Health Grants F32-HD-07885, T32-AG-00048, and RO1-HD-21212.

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