Delayed Visual Feedback and Movement Control in Parkinson’s Disease

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The dependence of movement on visual information was compared for healthy individuals and Stage II–III patients with Parkinson’s disease (PD). A time delay (0–1400 ms) was introduced into a visually guided motor tracking task which required the subject to maintain constant index finger position relative to a stationary baseline on an oscilloscope. For healthy individuals, delayed visual feedback induced complex oscillations in finger displacement. Similar results were obtained for four of eight patients with PD. However, oscillations were not induced in four of eight patients with PD because of reduced gain and/or a higher tremor amplitude at zero delay which obscured the tracking error. These results suggest that some patients with PD are able to utilize visual information for controlling tracking in this motor task in the same manner as healthy individuals.

INTRODUCTION

Patients with Parkinson’s disease (PD) have deficits in the planning and execution of voluntary movement (1). Normal voluntary movement consists of a ballistic component which is preprogrammed and executed without reference to sensory information (“open loop” control) and a corrective component whose course and/or termination are regulated by sensory feedback (“closed-loop” feedback control) (1, 2). A variety of clinical observations and experiments involving visually guided motor tracking tasks (3, 4) indicate that patients with PD cannot make fast ballistic movements, but are able to track targets accurately provided that they move slow enough (1, 5). Consequently, many investigators have searched for abnormalities in the open-loop control of movement as the basis for the motor abnormalities in PD (1, 2, 6). However, the interpretation of results derived from visually guided motor tracking tasks requires the assumption that visual information important for guiding movements is utilized normally in PD.

Visual perception (7, 8) and visual–motor adaptation to a pointing task during lateral displacement of vision by prism glasses (9) appear normal in nondemented patients with PD. However, there is evidence that the control of movement in both humans (10) and animals (11) with basal ganglia lesions has an increased dependence on visual information.

The dependence of movement on visual information in healthy subjects can be assessed by introducing a time delay into a visually guided motor tracking task (12–16). In experiments using long time delays (>100 ms) (14–16), subjects are required to adjust the position of their index finger to match the position of a visually displayed target. However, the subjects are only able to judge the position of their finger relative to the target at some time (i.e., 100 to 1400 ms) in the past. For young healthy subjects, introducing a visual delay in this manner leads to intermittently, regular oscillations in finger displacement with periods between two and four times the delay. The frequency of physiological tremor is unaffected by delayed visual feedback, suggesting that these oscillations are generated by more central control mechanisms (14–16). It is well known that oscillations arise because of the destabilizing effect of an increased delay on feedback control (17). The value of the delay for the onset of the oscillations in a feedback control loop as well as the frequency and amplitude of the oscillations depends sensitively on the properties of the control mechanism. Since these control mechanisms are affected in patients with PD we hypothesized that the performance of these patients in the movement task described above would differ markedly from that of healthy control subjects.

METHODOLOGY

Subjects

Twenty-four subjects were studied: eight medically treated patients with PD, ages 51 to 72 years (mean age = 58; Table 1); eight older subjects in good health, ages 42 to 70 (mean age = 57 years); and eight younger subjects in good health, ages 19 to 27 (mean age = 22 years). The clinical characteristics and stages (18) of the pa-
### Clinical Characteristics of Patients with Parkinson’s Disease

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age</th>
<th>Time since onset (years)</th>
<th>Stage</th>
<th>Tremor</th>
<th>Rigidity</th>
<th>Bradykinesia and gait abnormalities</th>
<th>Retropulsion</th>
<th>Anti-parkinson medication</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>51</td>
<td>6</td>
<td>3</td>
<td>Moderate rest tremor bilateral Lg and L &gt; R Ue mild essential tremor L &gt; R Ue</td>
<td>Moderate increase R &gt; L Ue</td>
<td>R &gt; L armswing start hesitation; slow walking</td>
<td>No</td>
<td>Prolopa 100/25 tid and 50/12.5 qd</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>54</td>
<td>5</td>
<td>3</td>
<td>No</td>
<td>Moderate increase L &gt; R Ue</td>
<td>L armswing; mild start hesitation</td>
<td>No</td>
<td>Symmetrel 100 mg qd; Benadryl 50 mg tid; Ativan 2 mg tid; Sinemet 100/25 tid; Artane 1 mg tid</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>60</td>
<td>18</td>
<td>3</td>
<td>Mild R &gt; L Ue Action tremor</td>
<td>Moderate increase R &gt; L Lg and Ue</td>
<td>R armswing; 2-3 steps without falling</td>
<td>No</td>
<td>Sinemet 250/25 5 times a day</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>53</td>
<td>11</td>
<td>2</td>
<td>Mild rest tremor R Ue and Lg Moderate L Ue rest tremor</td>
<td>Moderate increase R Ue</td>
<td>L armswing;</td>
<td>No</td>
<td>Sinemet 100 mg qd; Parlodel 5 mg tid; Prolopa 50/12.5 tid; Symmetrel 100 mg bid</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>72</td>
<td>6</td>
<td>1</td>
<td>Moderate rest tremor L Lg &gt; L Ue</td>
<td>Mild increase L Ue</td>
<td>L armswing;</td>
<td>No</td>
<td>Ativan 2 mg bid; Prolopa 50/12.5 tid; Symmetrel 100 mg bid; Artane 2 mg bid</td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>55</td>
<td>6</td>
<td>1</td>
<td>Moderate rest tremor L Lg &gt; L Ue</td>
<td>Mild increase L Ue</td>
<td>L armswing;</td>
<td>No</td>
<td>Sinemet 100/25 tid; Parlodel 2.5 mg bid; Artane 0.5 mg tid; Ativan 0.5-1 mg tid; Sinemet 100/25 qid; Benadryl 50 mg qid; Cogentin 2 mg tid</td>
</tr>
<tr>
<td>7</td>
<td>F</td>
<td>56</td>
<td>7</td>
<td>2</td>
<td>Mild–moderate rest tremor R &gt; L Ue</td>
<td>Mild–moderate increase R &gt; L Ue</td>
<td>R armswing; start hesitation</td>
<td>No</td>
<td>Prolopa 100/25 tid and 50/12.5 qd; Symmetrel 100 mg qd; Benadryl 50 mg qid; Cogentin 2 mg tid</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>66</td>
<td>15</td>
<td>3</td>
<td>Moderate rest tremor L Ue &gt; L Lg</td>
<td>Mild increase L Ue</td>
<td>L armswing; mild gait unsteadiness</td>
<td>No</td>
<td>Prolopa 100/25 tid and 50/12.5 qd; Symmetrel 100 mg qd; Benadryl 50 mg qid; Cogentin 2 mg tid</td>
</tr>
</tbody>
</table>

*Staging is according to the criteria of Hoehn and Yahr (18).

Patient 3 has marked variations in his clinical stage ("on-off" phenomena). An essential tremor was not seen at the time the experiment was performed.

Patients with PD are summarized in Table 1. These patients were of mixed type having various combinations of akinesia, rigidity, and tremor. The details of the experimental protocol were explained to each subject and they were then asked to sign a consent form. Normal subjects did not consume caffeinated beverages or medication during the 12 h preceding the experiment. Patients with Parkinson’s disease were generally studied in the morning and after the onset of action of their anti-parkinsonian medications. The stage of the patient at the time of the test, if different from that determined by history and repeated examinations, is also given in Table 1.

**Apparatus**

A schematic diagram of the experimental setup is shown in Fig. 1 and the experimental protocol is described in detail elsewhere (14–16). A linear variable displacement transducer (LVDT) was used to record microdisplacements of the index finger at the metacarlo-phalangeal joint (resolution of 0.023 mm). The position of the finger monitored by the LVDT was passed through an analog delay line (ADL) introducing time delays between 0 and 1400 ms. Upon leaving the ADL, the signal was filtered by an eight-pole low-pass Bessel filter with a corner frequency of 30 Hz. The position of the finger was hidden from the subject but was displayed on an oscilloscope placed directly in the field of vision of the subject and at a distance of 80 cm. An LVDT displacement of 1 mm corresponded to about 12 mm of vertical displacement on the oscilloscope. A stationary baseline was also displayed on the oscilloscope screen to act as a reference, or target, line.

**Test Procedure**

Each subject was seated in an upright position in a dark (faraday) room and was maintained in a stable posture with two seat belts. The tested forearm was supported in a trough with a 90° angle at the elbow. The index finger was extended and a fist was made around the thumb with the remaining three fingers. The entire hand was then secured in the trough such that the index finger extended beyond the end of the trough. A medical splint was placed onto the index finger and connected to the LVDT (Fig. 1).
The subjects were asked to align the oscilloscope line recorded via the LVDT from their index finger with the target line. Six tests were carried out on each subject corresponding to 300-, 600-, 800-, 1000-, 1200-, and 1400-ms time delays. The order of the tests was randomized for each subject. Two tests were performed at 0-ms delay: one at the beginning and one at the end of the testing session. Each testing session ended with the same test performed with eyes closed. The subjects were told that the tracking task would at times become more difficult to perform, but they were not informed that a time delay in visual feedback would be introduced. Each time delay was used only once and the trial lasted 60 s. Before each test the subject’s comfort was checked and the alignment of the finger with the LVDT was verified. Each test was preceded by an initial practice session of 15 s allowing the subject to stabilize the oscilloscope trace.

Data Analysis

A DataCraft A/D converter (7000 MDAS), and an Amiga microcomputer (A1000) were used for A/D conversion (at 150 Hz) and processing of the data was as described previously (16). The period of oscillations of the finger displacement was determined. The criterion for identifying the runs of regular oscillations in finger displacement for delays 600 ms and larger was the similarity of at last three consecutive waveforms (16). The interpeak interval was determined by measuring the average time between consecutive peaks during the regular oscillations. Since regular oscillations in finger displacement with delayed visual feedback occur only intermittently, the average interpeak interval for short time intervals does not provide a complete description of the time series for finger displacement for 60 s. One way to overcome this limitation is to calculate the average interpeak interval for the entire 60-s record. Preliminary measurements suggested that the average interpeak interval measured in this way did not markedly differ from that determined from only the runs of regular oscillations. However, this method of determining the average interpeak interval is subjective due to variability between investigators in identifying the peaks.

The fast-Fourier transform (FFT) was calculated on the first 8192 points at zero delay. The power was calculated for 4096 bins over the range 0 to 75 Hz (i.e., every 0.0183 Hz). The powers were then averaged over 5 bins and plotted with respect to the middle frequency of the 5 bins. Thus, there was a power point plotted every 0.091 Hz.

RESULTS

The effect of introducing a visual delay into the motor tracking task for younger and older healthy subjects is illustrated for 1000 ms in Fig. 2. As can be seen very irregular fluctuations in finger displacement occur which are not present at zero delay (Fig. 2). Intermittently there are runs of more regular, low-frequency oscillations in finger displacement. Similar observations were seen in all healthy subjects when the visual delay was greater than 300–600 ms. In four patients with PD (patients 3, 4, 6, and 7 in Table 1), introduction
The influence of delayed sensory feedback on motor skills in healthy individuals has been examined by previous investigators (18–22). Examples include the effects of delayed auditory feedback on speech and on vibrato in singers and the effects of delayed visual feedback on handwriting. Here we have studied the effect of delayed visual feedback on a motor task, focusing on the interactions between sensorimotor timing, control, and motor output.
delayed visual feedback on a simple motor tracking task involving the index finger in order to assess the utilization of visual information for movement by patients with PD.

In healthy individuals, introduction of a visual delay into this tracking task induces intermittently, regular oscillations in finger displacement (14-16). Qualitatively similar results were obtained for four of the eight patients with PD (Group I). However, although the remaining patients with PD (Group II) were able to maintain their finger relatively close to the target, regular oscillations in finger displacement did not occur as the delay in visual feedback was increased. The heterogeneity in the response of the patients with PD is not clearly correlated to differences in clinical history or frequency of the patient’s tremor, but appeared to be related to the amplitude of the patient’s tremor.

In a motor tracking task, visual input is required to attend to the target and to estimate the discrepancy, or error, between the position of the finger and the position of the target (23). This error gives rise to a signal which is fed back to the motor control mechanisms for finger movement to adjust finger position, thus minimizing the error. This cycle between perceived error and motor action forms a closed feedback loop. The gain of this feedback mechanism reflects the magnitude of the motor output induced by a given deviation of finger position from the target line. It is well known that oscillations can be produced by a feedback control mechanism that has been destabilized by an increase in the time

![Graphs showing data](image)

**FIG. 4.** Standard deviations for 5 12-s periods (1 through 5) of individual trials at zero (above) and 1000-ms (below) delays for younger control subjects (a, b), older control subjects (c, d), and patients with PD (e, f), respectively. Units are in volts and 0.1 V corresponds to 0.5 mm.

![Graphs showing data](image)

**FIG. 5.** Relationship between time delay (a) and period (b) of low-frequency oscillations for older (M) subjects (a), younger (N) subjects (b), and patients with PD (P) (c). As can be seen the average interpeak interval of the regular oscillation increases continuously with the time delay and is always between two and four times the delay.
patients with PD as the visual delay is increased. The fact that finger position was generally maintained close to the target throughout the 60-s trial suggests that these patients were attending to this task and understood it (25). In three of the Group II patients there was a large-amplitude high-frequency tremor (>5 Hz). In these patients the tracking error was so large and fluctuated so rapidly that tracking was difficult or impossible and slow oscillations were obscured (see Figs. 6a and 6b). In patient 2 with reduced resting tremor (Table 1) there was also no obvious low-frequency oscillations. This absence of low-frequency oscillation could be due to reduced gain of the visuomotor feedback loop. A physiological correlate of the reduced gain could be due to the fact that in voluntary movements in patients with PD the initial burst of agonist activity is typically smaller than that in normal controls (27) (Figs. 6c and 6d). In patient 1 there is a rapid oscillation of about 4.5 Hz and a regular waxing and waning of the oscillation at a frequency of about 0.5 Hz. One hypothesis is that the regular waxing and waning of the finger displacement occurs as a consequence of the interaction of the summation of two oscillations (i.e., essential and parkinsonian tremor) with slightly different frequencies resulting in a beat frequency (28) (Fig. 7).

One difference was observed between the time series of finger displacement for healthy individuals and some patients with PD. In the latter there were often apparently spontaneous transitions, occasionally abrupt, between runs of qualitatively different types of oscillations (Figs. 6c, 7a and 7c). Early investigators (29) showed that abrupt transitions from a 12-Hz tremor to a 6-Hz one could occur in a model of neural control mechanisms as certain parameters were varied. Since this time it has been well established in both model (14, 30–32) and experimental (15, 33) neural feedback mechanisms that a wide variety of complex dynamics can arise as certain parameters are varied. These observations raise the possibility that by carefully analyzing the complex time series we observe in our experiments in the context of simple, but appropriate, models for movement con-
trol, it may be possible to obtain better insights into the function of the basal ganglia.

A variety of paradigms have been used to evaluate the deficits in the execution of voluntary movement by patients with PD (1–5). The emphasis in these previous studies has been to compare the relative difficulty that patients with PD have in making fast movements versus slow movements. Although it is believed that sensory feedback plays a greater role in the control of slower movements (2–4), there have been few attempts to clarify the nature of this role.

In our experiment, subjects typically used relatively slow correction movements to match the position of their finger to the target. We cannot rule out the possibility that a short-term motor prediction could have been used by some subjects during the intermittent slow oscillation induced by the time delays. However, the subjects were not informed that a time delay would be inserted and they did not report its presence when asked about it after the testing session.

The errors in this motor tracking task are self-generated and arise from the subject's own tremor as well as from wrong decisions concerning the direction to move the finger. Previous studies have indicated that healthy individuals and patients with PD react to self-generated errors equally well and more quickly than to errors introduced by target movement (34). Thus, our paradigm is well suited to assess the role of sensory feedback for movement in PD since it minimizes the motor difficulties in these patients while maximizing the role of visual feedback.

Our observations suggest that, provided the amplitude of their tremor is small enough, patients with PD are able to utilize visual information for controlling tracking in this motor task in the same manner as healthy individuals. Thus, differences in performance of visually guided tracking tasks between healthy individuals and patients with PD cannot be ascribed to differences in the handling of visual information for motor control.

A task as simple as pointing a finger at a fixed target not only requires the intervention of most structures of the CNS involved in the control of movement but also produces dynamics that are extremely complex. Thus, by having this task performed by patients with well-localized pathological lesions of the CNS, it will become possible to examine the nature and role played by different control loops. By comparing the dynamics of finger displacements between patients and healthy subjects it should be possible to determine the role played by the damaged control loop(s). To dissect out each control loop and determine its type, it will be necessary to combine experimental results and theoretical simulations (14).

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REFERENCES